

## 2002 Electronics Materials Conference Grid

WEDNESDAY, JUNE 26<sup>TH</sup>

THURSDAY, JUNE 27<sup>TH</sup>

FRIDAY, JUNE 28<sup>TH</sup>

	AM	PM	AM	PM	AM	PM
Corwin Pavilion	<b>EMC Plenary Lecture/Student Awards</b>	<b>REGISTRATION</b> 3:00PMñ5:00PM, Tuesday, June 25, 2002, Multicultural Lounge 7:30AMñ5:00PM, Wednesday, June 26, 2002, Multicultural Lounge 7:30AMñ4:00PM, Thursday, June 27, 2002, Multicultural Lounge 7:30AMñ10:00AM, Friday, June 28, 2002, Multicultural Lounge			<b>EXHIBITS</b> 9:15AMñ4:00PM & 7:00PMñ9:00PM, Wednesday, June 26, 2002, Lagoon Plaza 9:00AMñ4:00PM, Thursday, June 27, 2002, Lagoon Plaza	
Corwin East			Session U. Silicon Carbide: Growth	Session BB. Porous Semiconductors: Fabrication, Properties, and Applications	Session II. Silicon Carbide: Defects	Session NN. Metal Contacts to Semiconductors
Corwin West			Session T. Special Topical Session: Semiconductor Spintronics II	Session AA. Nanoscale Fabrication and Self-Assembly	Session HH. Nanostructures	Session MM. Novel Fabrication of Nanostructures
Lotte Lehmann	Session A. Nitride Epitaxial Growth	Session G. Nitrides: Light Emitters and Piezoelectric Effects	Session M. Nitrides: Dislocation Reduction and Characterization	Session V. Nitride Doping and Defects	Session CC. Nitride Device Processing: Contacts, Etching, and Dielectrics	Session JJ. Wide Bandgap Substrates and Surfaces
MultiCultural Theatre	Session B. Molecular Electronics	Session H. Organic Semiconductors: Materials and Devices	Session N. Photonic Bandgap Materials and Devices	Session W. Organic and Amorphous Semiconductors: Materials and Devices	Session DD. Biological/Electronic Interfaces	Session KK. Non-Destructive Testing and <i>In-Situ</i> Monitoring and Control
UCEN Flying A	Session E. Materials Integration: Wafer Bonding and Alternative Substrates I	Session K. Materials Integration: Wafer Bonding and Alternative Substrates II				
UCEN Harbor	Session D. Antimonide-Based Materials and Devices I	Session J. Antimonide-Based Materials and Devices II	Session P. Quantum Wells and Superlattices	Session Q. Quantum Dot Devices	Session GG. Semiconductors: Processing and Oxidation	
UCEN Lobero	Session F. Silicon Carbide: Processing	Session L. Nitrides: Transport and Devices	Session R. Epitaxy: Metamorphic/Strain	Session Y. Epitaxy: Arsenide Nitrides		
UCEN State Street	Session C. Nanoscale Characterization	Session I. Special Topical Session: Semiconductor Spintronics I	Session O. Gate Dielectrics I	Session X. Gate Dielectrics II	Session EE. Oxide Heteroepitaxy	Session LL. Epitaxial Oxides on Silicon
					Session FF. Si-Based Heterojunction Growth and Characterization	

# 2002 EMC AT-A-GLANCE

## Wednesday Morning, June 26, 2002

**8:20 AM** EMC PLENARY LECTURE/STUDENT AWARDS

**Room:** Corwin Pavillion

**Plenary Speaker:** David Awschalom  
University of CaliforniañSanta Barbara

**Topic:** "Manipulating Quantum Information with Semiconductor Spintronics"

**Break:** 9:20 AMñ10:00 AM

<b>Session A: Nitride Epitaxial Growth</b>	<b>Session B: Molecular Electronics</b>	<b>Session C: Nanoscale Characterization</b>
<p>10:00 AM <b>A1, The Growth and Characterization of High-Quality AlGaIn on Sapphire for Deep UV Emitters</b> ..... Jianping Zhang</p> <p>10:20 AM <b>A2, InGaIn-Channels for Field Effect Transistor Application</b> ..... Matthias Seyboth</p> <p>10:40 AM <b>A3, Intersubband Absorption Observation Ranging the Whole Communication Wavelength (<math>\approx</math>1.1-1.6 <math>\mu</math>m) with FWHM of 111-61meV in GaN/AlN Multiple Quantum Wells</b> ..... Katsumi Kishino</p> <p>11:00 AM <b>A4 (Student), Electrical and Optical Properties of InN Grown by MBE</b> ..... Hai Lu</p> <p>11:20 AM <b>A5 (Student), Characteristics of GaN Epitaxial Layers Grown on GaN and AlN Buffers by RF Molecular Beam Epitaxy</b> ..... Gon Namkoong</p> <p>11:40 AM <b>A6, Late News</b></p>	<p>10:00 AM <b>B1 (Student), Large Area Metal/SAM/Metal Devices by Oblique Evaporation</b> ..... Chung-Chen Kuo</p> <p>10:20 AM <b>B2 (Student), Electrical Contacts to Molecular Layers Using Pre-formed Pads</b> ..... Srinivasan Kadathur</p> <p>10:40 AM <b>B3 (Student), Contact Effects on the Resistance of Molecular Junctions</b> ..... Jeremy M. Beebe</p> <p>11:00 AM <b>B4 (Student), Electrical Characterization of In-Wire Molecular Electronic Devices</b> ..... James B. Mattzela</p> <p>11:20 AM <b>B5, Rectifying Molecular Diodes from Self-Assembly on Silicon</b> ..... Dominique Vuillaume</p> <p>11:40 AM <b>B6, A Nanostructured Gas Sensor: Coupling a Selective Molecular Level Event to an External Circuit</b> ..... Jaewon Choi</p>	<p>10:00 AM <b>C1, Two-Photon Laser Scanning Microscope for UV Spectroscopy and Lithography</b> ..... Julia W. Hsu</p> <p>10:20 AM <b>C2 (Student), Cross-Sectional Scanning Tunneling Microscopy Studies of Phase Separation in InP/GaP Short Period Superlattices</b> ..... Byungha Shin</p> <p>10:40 AM <b>C3 (Student), Variation of Interface Structure in InGaAs/InP Heterostructures Studied by Scanning Tunneling Microscopy</b> ..... H. A. McKay</p> <p>11:00 AM <b>C4 (Student), Indium-Indium Pair Correlations Within the Wetting Layers of Buried InAs/GaAs Quantum Dots</b> ..... Byungha Shin</p> <p>11:20 AM <b>C5 (Student), Nano-Faceting of the GaAs(311) Surface</b> ..... Vahid Yazdanpanah</p> <p>11:40 AM <b>C6, Compositional Analysis of Graded Al<sub>x</sub>Ga<sub>(1-x)</sub>As Layers by X-Ray Energy Dispersive Spectrometry</b> ..... Krishnamurthy Mahalingam</p>

# 2002 EMC AT-A-GLANCE

## Wednesday Morning, June 26, 2002

<b>Session D: Antimonide-Based Materials &amp; Devices - I</b>	<b>Session E: Materials Integration: Wafer Bonding and Alternative Substrates - I</b>	<b>Session F: Silicon Carbide: Processing</b>
<p>10:00 AM D1, Growth of GaAsSb/GaAs Double Quantum Well Lasers Emitting Near 1.3 <math>\mu\text{m}</math> ..... Irene C. Ecker</p> <p>10:20 AM D2 (Student), Characterization of Effects of Various Barrier Materials on GaAsSb 1.3<math>\mu\text{m}</math> QW Heterostructures Grown by Metalorganic Chemical Vapor Deposition ..... Min S. Noh</p> <p>10:40 AM D3 (Student), MBE Growth and Device Performance of GaAsSb Resonant-Cavity-Enhanced Avalanche Photodiodes with Separate Absorption, Charge and Multiplication Regions ..... X. Sun</p> <p>11:00 AM D4 (Student), Optically Pumped AlGaInSb/GaInSb Multiple Quantum Well Lasers ..... Edwin Pease</p> <p>11:20 AM D5, Physics of Sb-Heterostructure Quantum Tunneling Millimeter Wave Diodes ..... J. N. Schulman</p> <p>11:40 AM D6, InSb Heterostructure Bipolar Transistor Operating at Room Temperature ..... T. J. Phillips</p>	<p>10:00 AM E1, Testing the Feasibility of Strain Relaxed Compliant Substrates ..... M. Kostrzewa</p> <p>10:20 AM E2 (Student), High Ge-Content Relaxed Si<sub>1-x</sub>Ge<sub>x</sub> Layers by Relaxation on Compliant Substrate with Controlled Oxidation ..... Haizhou Yin</p> <p>10:40 AM E3, Strain Relaxation in Wafer-Bonded SiGe/Si Heterostructures Due to Viscous Flow of an Underlying Borosilicate Glass ..... Peter Morán</p> <p>11:00 AM E4, Ultra High Precision of the Tilt/Twist Misorientation Angles in Silicon/Silicon Direct Wafer Bonding ..... F. Fournel</p> <p>11:20 AM E5, Observation and Simulation of Anisotropic Diffusion of Hydrogen at Hydrophobic Wafer Bonded Interface ..... Robert Esser</p> <p>11:40 AM E6, The Effects of Plasma Exposure Used for Bonding on the Electrical Characteristics of the Treated Wafers ..... Cindy Colinge</p>	<p>10:00 AM F1, Temperature Dependence of Channel Mobility in Nitric Oxide Annealed MOSFETs on (0001) 4H-SiC ..... Chao Y. Lu</p> <p>10:20 AM F2 (Student), The Effect of Crystal Orientation and Post-Oxidation NO Anneal on Inversion Layer Electron Mobility in 4H-SiC UMOFETs ..... Imran A. Khan</p> <p>10:40 AM F3, Bonding Changes Across the Silicon Dioxide-Silicon Carbide Interface: Effect of Oxidation Temperature and Reoxidation Conditions ..... Kai-Chieh Chang</p> <p>11:00 AM F4, Low-Dose Nitrogen N-Type Implants in 4H-SiC ..... Nelson Saks</p> <p>11:20 AM F5 (Student), Laser-Direct Write and Doping of Wide Bandgap Materials ..... Islam Salama</p> <p>11:40 AM F6, Late News</p>

# 2002 EMC AT-A-GLANCE

## Wednesday Afternoon, June 26, 2002

<b>Session G: Nitrides: Light Emitters and Piezoelectric Effects</b>	<b>Session H: Organic Semiconductors: Materials and Devices</b>	<b>Session I: Special Topical Session: Semiconductor Spintronics - I</b>
1:20 PM G1 (Student), AlGaIn/GaN and AlGaIn/AlGaIn UV Light-Emitting Diodes Grown by Metalorganic Chemical Vapor Deposition ..... Ting G. Zhu	1:20 PM H1 Invited, Carrier Heating in Molecular Crystals: Negative Differential Mobility in Pentacene ..... E. M. Conwell	1:20 PM I1 (Student), Growth and Magnetic Properties of Digital Ferromagnetic Heterostructures Prepared by Atomic Layer Epitaxy ..... Ezekiel Johnston-Halperin
1:40 PM G2, Structural, Electrical and Optical Properties of Deep Ultraviolet AlInGaInN Light Emitting Diodes ..... Sergey Nikishin	2:00 PM H2, Transient Conductance in Organic Transistors ..... Robert Street	1:40 PM I2 Invited, Ab-Initio Transport in Digital Ferromagnetic Heterostructures ..... Stefano Sanvito
2:00 PM G3 (Student), Surface-Emitting Light-Emitting Diode with a GaN Tunnel-Junction Current Aperture ..... Jeon Seong-Ran	2:20 PM H3, Organic Thin Film Transistors with Polymer Gate Dielectric Layer and Carrier Mobility of 0.5 cm <sup>2</sup> /V-s ..... Hagen Klauk	2:20 PM I3 (Student), Transport and Magnetic Studies of Digital (Ga,Mn)As Heterostructures: Spacer-Dependence, Growth Temperature Dependence and Carrier Concentrations ..... T. C. Kreutz
2:20 PM G4, The Influence of Indium Incorporation on the Optical, Photoluminescence and Lasing Properties of InGaIn, AlInGaIn Films and Quantum Well Structures ..... M. Y. Ryu	2:40 PM H4, Contact Resistance of OTFTs with Different Device Designs ..... David J. Gundlach	2:40 PM I4, Effects of Disorder and Frustration on Ferromagnetism in Diluted Magnetic Semiconductors ..... Ravindra N. Bhatt
2:40 PM G5 (Student), GaN Microdisk Fabrication Using Photoelectrochemical Etching ..... Elaine D. Haberer	3:00 PM H6 (Student), Designing Organic Semiconductors: A Case Study Using Quinoid Oligo-thiophenes ..... Reid J. Chesterfield	3:00 PM I5 Invited, Correlation of the Mn Lattice Location, Free Hole Concentration and Curie Temperature in Ferromagnetic GaMnAs ..... Kin Man Yu
3:00 PM Break	3:20 PM H5, Functionalized Acenes for Improved Electronic Properties ..... John E. Anthony	3:20 PM I6 (Student), Ferromagnetic Ga <sub>1-x</sub> Mn <sub>x</sub> As and Ga <sub>1-x</sub> Mn <sub>x</sub> As <sub>1-y</sub> C <sub>y</sub> Produced by Ion Implantation and Laser Annealing ..... Michael A. Scarpulla
3:20 PM G6, Recombination Dynamics of Localized Excitons in Cubic In <sub>x</sub> Ga <sub>1-x</sub> N/GaN Multiple Quantum Wells on 3C-SiC/Si (001) ..... Shigefusa Chichibu	3:40 PM H7 (Student), Organic Thin Film Transistors Based on Functionalized Pentacene Active Layers ..... Chris D. Sheraw	4:00 PM I7, Electronic Structure and Spin-Polarization of MnGaIn ..... Leeor Kronik
3:40 PM G7, Molecular-Beam Epitaxial Growth and Piezoelectric Investigation Under Applied Biaxial Stress of (In,Ga)N/GaN Multiple-Quantum Wells ..... Patrick Waltereit	4:20 PM H8, Charge Injection in Organic Semiconductors ..... George G. Malliaras	4:20 PM I8, Late News
4:00 PM G8 (Student), Nonlinear Piezoelectric Effect in GaN/AlGaIn Quantum Wells ..... Georgiy Vaschenko	4:40 PM H9, Late News	
4:20 PM G9 (Student), Piezoelectric Coefficients of III-V Wurtzite Nitrides ..... Philip Tavernier		
4:40 PM G10 (Student), Polarization Bulk Doping in Graded AlGaIn Alloys ..... Debdeep Jena		

# 2002 EMC AT-A-GLANCE

## Wednesday Afternoon, June 26, 2002

<b>Session J: Antimonide-Based Materials and Devices - II</b>	<b>Session K: Materials Integration: Wafer Bonding and Alternative Substrates – II</b>	<b>Session L: Nitrides: Transport and Devices</b>
<p>1:20 PM J1, Anion Exchange Reactions and Isoelectronic AsSb Formation: GaSb<sub>y</sub>As<sub>1-y</sub>/GaAs and GaAs<sub>y</sub>Sb<sub>1-y</sub>/GaSb Superlattice Interface Quality ..... Maria Losurdo</p> <p>1:40 PM J2 (Student), Characterization of Anion Exchange for Mixed Group V Heterostructures During Molecular Beam Epitaxy ..... Terence Brown</p> <p>2:00 PM J3, Surfactant Effects on the Nucleation of InAsSb Semiconductor Nanostructures ..... Jeff Cederberg</p> <p>2:20 PM J4 (Student), Self Assembled Quantum Wires in GaAs/GaSb Short Period Superlattices ..... Catalina I. Dorin</p> <p>2:40 PM J5 (Student), Identification of Type I Offset Behavior in AlInAsSb/InAsSb MQW Structures ..... Leslie Vaughn</p> <p>3:00 PM Break</p> <p>3:20 PM J6, The Preparation of InGa(As)Sb &amp; Al(Ga)AsSb Films &amp; Diodes on GaSb for Thermophotovoltaic Applications Using Metal-Organic Chemical Vapor Deposition ..... Jeff Cederberg</p> <p>3:40 PM J7, Reduction of the Interface Recombination Rate in GaInAsSb/GaSb Broken-Gap Heterostructures ..... Dmitri Donetsky</p> <p>4:00 PM J8, Comparing Pseudopotential Predictions for InAs/GaSb Superlattices ..... Gregory Dente</p> <p>4:20 PM J9 (Student), Chlorine Doping in ZnMgSe: Theory and Experiment ..... Brenda Vanmil</p> <p>4:40 PM J10, High Mobility and 9.5 Micron Cut-Off Wavelength InAsSb Films Grown on Semi-Insulating GaAs by Liquid Phase Epitaxy ..... V. K. Dixit</p>	<p>1:20 PM K1 (Student), Wafer Bonding for III-V on Insulator Structures ..... S. Hayashi</p> <p>1:40 PM K2, Wafer Bonded InP/Si and InP/Ge for 4-Junction Solar Cell Heterostructures ..... Anna Fontcuberta Morral</p> <p>2:00 PM K3, Wafer Bonded Ge/Si Substrates for Triple Junction Solar Cell Structures ..... James M. Zahler</p> <p>2:20 PM K4 (Student), Long Wavelength InGaAs/InAlAs/InP-GaAs/AlGaAs Avalanche Photodiode Implemented by Direct Wafer Bonding ..... J. B. Hurst</p> <p>2:40 PM K5, Wafer Fusion Enables the First AlGaAs/GaAs/GaN Double Heterojunction Bipolar Transistor (DHBT) ..... Sarah Estrada</p> <p>3:00 PM Break</p> <p>3:20 PM K6, Heterogeneous Assembly of III-V Devices onto Silicon Using Electro-Fluidic Assembly ..... Christopher Nordquist</p> <p>3:40 PM K7 (Student), Monolithic Integration of Lattice-Mismatched Semiconductors with Si via Wafer Bonding ..... Arthur J. Pitera</p> <p>4:00 PM K8, (Student), Silicon on Diamond Formed by Wafer Bonding ..... Gleb N. Yushin</p> <p>4:20 PM K9 (Student), A Metallic Bonding Method for the Fabrication of Long-Wavelength VCSELs ..... Hung C. Lin</p> <p>4:40 PM K10, Improvements in Wafer-Bonded AlGaInP Light-Emitting Diodes by Various Mirror Substrates ..... Ray H. Horng</p>	<p>1:20 PM L1, Comparative Study of AlGaN/GaN HEMTs Grown by MBE on Semi-Insulating HVPE GaN Templates and Directly on Sapphire ..... M. J. Manfra</p> <p>1:40 PM L2 (Student), High Performance AlGaN/GaN HEMTs on Semi-Insulating SiC Substrates Grown by Metalorganic Chemical Vapor Deposition ..... Michael M. Wong</p> <p>2:00 PM L3 (Student), AlGaN/GaN HEMTs on Fe doped Semi-Insulating GaN: Material and Device Characteristics ..... Sten Heikman</p> <p>2:20 PM L4, Layer Structure Optimization for AlGaN/GaN HFET Applications ..... Delphine Sicault</p> <p>2:40 PM L5 (Student), Investigation of Traps in Doped and Undoped AlGaN/GaN HEMTs ..... Mike Wolter</p> <p>3:00 PM Break</p> <p>3:20 PM L6, High DC and RF Performances of High Al-Content AlGaN/GaN HEMTs with 0.25µm Gate ..... Mi-Ran Park</p> <p>3:40 PM L7 (Student), Elimination of Current Collapse of AlGaN/GaN HEMTs with MgO, and Sc<sub>2</sub>O<sub>3</sub> ..... Ben Luo</p> <p>4:00 PM L8 (Student), High Detectivity Solar-Blind AlGaN Photodetectors Grown by Metalorganic Chemical Vapor Deposition ..... Uttiya Chowdhury</p> <p>4:20 PM L9 (Student), AlGaN/Sapphire Epilayers for Acoustic Wave Devices ..... Tomás Palacios</p> <p>4:40 PM L10, Late News</p>

# 2002 EMC AT-A-GLANCE

## Thursday Morning, June 27, 2002

<b>Session M: Nitrides: Dislocation Reduction and Characterization</b>	<b>Session N: Photonic Bandgap Materials and Devices</b>	<b>Session O: Gate Dielectrics - I</b>
<p>8:20 AM M1, Evolution of Microscopic Growth Domains and Mg Incorporation During Maskless Epitaxial Lateral Overgrowth of AlGaIn on Patterned Sapphire ..... Frank Bertram</p> <p>8:40 AM M2, Facet Controlled Growth in Cantilever Epitaxy for Improved LED Performance ..... Andrew A. Allerman</p> <p>9:00 AM M3, Crack-Free Thick AlGaIn Layers Grown on GaN Using Strain-Relief Interlayers ..... Changqing Chen</p> <p>9:20 AM M4, Impact of In-Situ Si<sub>3</sub>N<sub>4</sub> Nano-Masks on Blue GaN Based Light Emitting Diodes on Si(111) ..... A. Dadgar</p> <p>9:40 AM M5, Reducing Threading Dislocations in Laterally Grown GaN: Further Approaches ..... David M. Follstaedt</p> <p>10:00 AM Break</p> <p>10:20 AM M6, Investigation of the Heteroepitaxial Growth of GaN Directly on SiC(0001) by Plasma-Assisted Molecular Beam Epitaxy ..... Patrick Waltereit</p> <p>10:40 AM M7, Crystalline Qualities and Optical Properties of MBE-Grown GaN/AlN Multiple Quantum Wells for Intersubband Transition ..... Kei Kaneko</p> <p>11:00 AM M8, Dislocation Density and Electrical Compensation in GaN Films ..... Mark E. Twigg</p> <p>11:20 AM M9 (Student), Limitation of the Lattice Thermal Conductivity of GaN Films by Threading Dislocations and Point Defects ..... Jie Zou</p> <p>11:40 AM M10 (Student), Determination by Electron Holography of the Charge Distribution in Threading Dislocations in Epitaxial GaN ..... Juan Cai</p>	<p>8:20 AM N1 Invited, Dispersion and Dispersion Control in Photonic Crystals ..... Shanhui Fan</p> <p>9:00 AM N2 Invited, On-Chip Assembly of Silicon Photonic Band Gap Crystals ..... David J. Norris</p> <p>9:40 AM N3, Creating Periodic 3D Structures by Multi-Beam Interference ..... Shu Yang</p> <p>10:00 AM Break</p> <p>10:20 AM N4 Invited, 2-D Unit-Cell Photonic Band Gap Nanolasers ..... Y. H. Lee</p> <p>11:00 AM N5 Invited, Promises of Photonic Crystals Revisited: The Case of III-V 2D Photonic Crystals ..... Claude Weisbuch</p> <p>11:40 AM N6, High Accuracy FDTD Calculation of Pulse Compression in a Finite Photonic Crystal Waveguide ..... James B.B. Cole</p>	<p>8:20 AM O1 Invited, Interface and Materials Properties of High-K Gate Stack Structures ..... Eric L. Garfunkel</p> <p>9:00 AM O2, Layered Tunnel Barriers for Silicon Based Nonvolatile Memory Applications ..... Julie D. Casperson</p> <p>9:20 AM O3, Structure and Stability of Alternative High-K Dielectric Layers on Silicon ..... Susanne Stemmer</p> <p>9:40 AM O4 (Student), Radiation Induced Interface Traps in MOS Devices: Capture Cross Sections and the Density of States of P<sub>bt</sub> Silicon Dangling Bond Centers ..... Nathaniel A. Bohna</p> <p>10:00 AM Break</p> <p>10:20 AM O5, Thermally Stable Single Layer Hafnium Silicate Films for Gate Dielectric Application ..... S. Gopalan</p> <p>10:40 AM O6, Late News</p>

# 2002 EMC AT-A-GLANCE

## Thursday Morning, June 27, 2002

<b>Session P: Quantum Wells and Superlattices</b>	<b>Session R: Epitaxy: Metamorphic/Strain</b>	<b>Session T: Special Topical Session: Semiconductor Spintronics - II</b>
<p>8:20 AM P1 Invited, Structural and Optical Properties of (In,Ga)N/GaN Quantum Wells Grown by Plasma-Assisted Molecular Beam Epitaxy ..... O. Brandt</p> <p>9:00 AM P2, Intersubband and Interband Optical Absorption Study of Strain-Compensated InGaAs-InGaP Superlattices Grown on GaAs ..... Mykhaylo Semtsiv</p> <p>9:20 AM P3 (Student), Effects of Annealing on the Lateral Ordering of InAs/GaAs Quantum Dot Superlattices ..... Wenzhou Chen</p> <p>9:40 AM P4, Growth and Characterization of IV-VI Semiconductor Multiple Quantum Well Structures ..... Patrick J. McCann</p> <p>10:00 AM Break</p>	<p>8:20 AM R1 (Student), Evolution of Surface Morphology and Stress Relaxation in <math>\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaAs}</math> ..... Benny Perez-Rodriguez</p> <p>8:40 AM R2 (Student), Growth of Compositionally-Graded InAlAs and InAsP Buffer Layers on InP Substrates Using Solid Source Molecular Beam Epitaxy ..... Yong Lin</p> <p>9:00 AM R3 (Student), Growth and Polishing of InAlAs Graded Buffer Layers for InAs-Based Device Structures ..... A. M. Noori</p> <p>9:20 AM R4 (Student), Influence of Growth Parameters on Antimony Incorporation During Molecular Beam Epitaxy of III-Arsenide-Antimonides ..... Rubin Sidhu</p> <p>9:40 AM R5, Micro-X-Ray Fluorescence and Micro-Photoluminescence in Quaternary Layers Obtained by Selective Area Growth ..... Andrei Sirenko</p> <p>10:00 AM Break</p>	<p>8:20 AM T1 Invited, Epitaxial Growth and Properties of Ferromagnetic Co-Doped <math>\text{TiO}_2</math> ..... Anatase S.A. Chambers</p> <p>9:00 AM T2, Electric-Field Effects on Spin Diffusion and Enhancement of Spin Injection into Semiconductors ..... Zhi G. Yu</p> <p>9:20 AM T3, Spin Coherent Electron Injection in a Self Assembled Nanowire with Ferromagnetic Nanocontacts: A Novel Route to Single Qubit Rotation in a Quantum Gate ..... Supriyo Bandyopadhyay</p> <p>9:40 AM T4, Tunability of Electron Spin Coherence in Semiconductor Nanostructures ..... Wayne H. Lau</p> <p>10:00 AM Break</p> <p>10:20 AM T5 (Student), <math>\text{Fe}_{1-x}\text{Co}_x/\text{GaAs}</math> Interfaces: Growth, Interfacial Reactions and Spin Polarized Transport ..... B. D. Shultz</p> <p>10:40 AM T6, Direct Spin Injection from a Ferromagnetic Metal into a Semiconductor Through Fe/InAs Junction ..... Kanji Yoh</p> <p>11:00 AM T7, Spin-Spin Interaction in Magnetic Semiconductor Quantum Dots ..... Gerd Bacher</p> <p>11:20 AM T8, Field Effect Magnetization Reversal in Ferromagnetic Semiconductor Quantum Wells ..... Byounggak Lee</p> <p>11:40 AM T9, Late News</p>
<b>Session Q: Quantum Dot Devices</b>	<b>Session S: Epitaxy: Doping and Defects</b>	
<p>10:20 AM Q1 Invited, InAs Quantum Dot Infrared Photodetectors ..... Joe C. Campbell</p> <p>11:00 AM Q2 (Student), Low-Threshold InP Quantum-Dot Lasers Coupled to Strained InGaP Quantum Wells Grown by Metalorganic Chemical Vapor Deposition ..... Richard D. Heller</p> <p>11:20 AM Q3 (Student), 1.3-Micron InAs Quantum Dot Laser with <math>T_0 = 213</math> K from 0 to 80°C ..... Oleg B. Shchekin</p> <p>11:40 AM Q4, Evaluation of Performance Limitations in Quantum Dot Infrared Detectors ..... Jamie D. Phillips</p>	<p>10:20 AM S1 (Student), Tellurium-Induced Disordering of Cu-Pt Type Ordered Structures in <math>\text{In}_{0.5}(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{P}</math> Layers ..... Kuo-Lih Chang</p> <p>10:40 AM S2 (Student), Minority Carrier Lifetime Studies in Heavily Beryllium-Doped P-Type GaAs ..... Thomas D. Boone</p> <p>11:00 AM S3, Acceptor Doping Properties in <math>(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}</math> and AlGaInN ..... P. N. Grillo</p> <p>11:20 AM S4 (Student), Fast Photoconductive Materials Pumped at 1.55<math>\mu\text{m}</math>:ErAs:InGaAs.....Daniel C. Driscoll</p> <p>11:40 AM S5 (Student), Arsenic Incorporation in Si Molecular Beam Epitaxy ..... Xian Liu</p>	

# 2002 EMC AT-A-GLANCE

## Thursday Afternoon, June 27, 2002

<b>Session U: Silicon Carbide: Growth</b>	<b>Session V: Nitride Doping and Defects</b>	<b>Session W: Organic and Amorphous Semiconductors: Materials and Devices</b>
<i>Thursday Morning, Cont.</i>		
<p>8:20 AM U1, Comparison of N-Type SiC Epitaxial Layers Grown Using Phosphine and Nitrogen as the Precursors ..... Ishwara Bhat</p> <p>8:40 AM U2, Characterization of 3C-SiC Layers Grown During Step-Free Surface Heteroepitaxy ..... Philip G. Neudeck</p> <p>9:00 AM U3, Electrical and Structural Properties of Al-Doped 4H-SiC Epitaxial Layers-Grown by Hot-Wall CVD ..... Günter Wagner</p> <p>9:20 AM U4 (Student), Characterization of Undoped and Nitrogen-Doped 4H-SiC Thin Films by CVD from Bis-trimethylsilylmethane Single Precursor ..... Jae Kyeong Jeong</p> <p>9:40 AM U5, Late News</p> <p>10:00 AM Break</p> <p>10:20 AM U6, P- and N-Type Doping of Silicon Carbide Single Crystals Using a Modified Physical Vapor Transport Technique ..... Peter J. Wellmann</p> <p>10:40 AM U7, Semi-Insulating Bulk Single Crystals of 6H Silicon Carbide ..... A. Gupta</p> <p>11:00 AM U8, Comparative Characterization of Differently Oriented SiC Wafers ..... Peter G. Muzykov</p> <p>11:20 AM U9, Modeling of In-Situ Off-Axis Seeding Surface Preparation Conditions for SiC PVT Growth ..... Roman V. Drachev</p> <p>11:40 AM U10, Late News</p>	<p>1:20 PM V1 (Student), Growth and Impurity Incorporation in InGaN Grown by RF-Plasma Assisted Molecular Beam Epitaxy (MBE) ..... Christiane Poblenz</p> <p>1:40 PM V2 (Student), Si Doping of High Al Mole Fraction <math>Al_xGa_{1-x}N</math> Alloys with RF Plasma MBE ..... Jeonghyun Hwang</p> <p>2:00 PM V3, More Efficient P-Doping for GaN? ..... An-Ban Chen</p> <p>2:20 PM V4, Effect of Electron Irradiation on Growth and Properties of GaN Grown by RF Plasma Molecular Beam Epitaxy ..... Dimitris Korakakis</p> <p>2:40 PM V5, Defects Introduced in GaN/AlGaIn HEMT Structures from SiC Substrate Defects ..... B. D. Poust</p> <p>3:00 PM Break</p> <p>3:20 PM V6, Heterogeneous Integration of Low Dislocation Density III-Nitride Epitaxial Material on Silicon-On-Insulator (SOI) Substrates ..... Joseph E. Van Nostrand</p> <p>3:40 PM V7, Reverse-Bias Leakage Current Reduction in GaN Schottky Diodes by Surface Modification with an Atomic Force Microscope ..... Eric J. Miller</p> <p>4:00 PM V8 (Student), High Energy Proton Irradiation of MgO/GaN Metal Oxide Semiconductor Diodes ..... Jihyun Kim</p> <p>4:20 PM V9, Late News</p> <p>4:40 PM V10, Late News</p>	<p>1:20 PM W1, Jet-Printed Fabrication of Amorphous Silicon Thin-Film Transistors and Arrays ..... William S. Wong</p> <p>1:40 PM W2 (Student), Phosphorescent OLED Amorphous Silicon TFT Active-Matrix Pixel ..... Jonathan Nichols</p> <p>2:00 PM W3 (Student), Development of New Blue Light Emitting Material and its Device Characteristics ..... Seungmoon Pyo</p> <p>2:20 PM W4, Energy Transfer and Triplet Exciton Confinement in Phosphorescent Polymer Light-Emitting Diodes ..... Fang-Chung Chen</p> <p>2:40 PM W5, Blue Luminescence from Thin Films of Tris(8-Hydroxyquinoline) Aluminium(III) ..... Michele Muccini</p> <p>3:00 PM Break</p> <p>3:20 PM W6 (Student), Morphology and Impurity Effects in Pentacene Thin-Film Transistors ..... Stijn Verlaak</p> <p>3:40 PM W7, In Situ Monitor on the Re-Orientation of Molecular Chains in Operating Organic Devices ..... Tzung-Fang Guo</p> <p>4:00 PM W8 (Student), Electron Diffraction and High Resolution Electron Microscopy of Orthorhombic Crystals in Thermally Evaporated Pentacene Thin Films ..... Lawrence Drummy</p> <p>4:20 PM W9, Ceramic Superconductor/Organic Polymeric Conductor Nano-Structures. ..... Steen B. Schougaard</p> <p>4:40 PM W10, Optical Switching Responses of Polymer-Based Phototransistors ..... K. S. Narayan</p>



# 2002 EMC AT-A-GLANCE

## Thursday Afternoon, June 27, 2002

<b>Session X: Gate Dielectrics - II</b>	<b>Session Y: Epitaxy: Arsenide Nitrides</b>	<b>Session AA: Nanoscale Fabrication and Self-Assembly</b>
<p>1:20 PM X1 Invited, Electronic Structure of Conduction Band States in Transition Metal Oxide, Silicate and Aluminate Alternative High-K Gate Dielectrics ..... G. Lucovsky</p> <p>2:00 PM X2, EXAFS Measurements of Crystallization of ZrO<sub>2</sub> Dielectric Films ..... Charles Bouldin</p> <p>2:20 PM X3, Structure and Stability of Gd- and La-Based High-K Films on Si(100) ..... Xiaohua Wu</p> <p>2:40 PM X4 (Student), An Electron Spin Resonance Observation of Hafnium Oxide Thin Films for Advanced Gate Dielectrics ..... Andrew Y. Kang</p> <p>3:00 PM Break</p> <p>3:20 PM X5, Physical and Electrical Characteristics of ZrO<sub>2</sub> Thin Films as a Promising Gate Dielectrics ..... Jung-Ho Yoo</p> <p>3:40 PM X6, The Characteristics of HfO<sub>2</sub> Thin Films as Gate Dielectrics ..... Seok-Woo Nam</p> <p>4:00 PM X7, Interfacial Reaction Between Poly SiGe and ZrO<sub>2</sub> with Ge Content in the Poly SiGe Films ..... Sung-Kwan Kang</p> <p>4:20 PM X8 (Student), Electrical and Materials Characteristics of Pr<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> ..... Sanghun Jeon</p> <p>4:40 PM X9, Atomic Layer Deposition of ZrO<sub>2</sub> Thin Films ..... Anil Mane</p>	<p>1:20 PM Y1 (Student), Effects of Arsenic Flux on the Stress Evolution and Optical Properties of GaAsN Films Grown by Reactive Molecular Beam Epitaxy ..... Matthew Reason</p> <p>1:40 PM Y2 (Student), Strain-Induced Valence Band Splitting in Bulk GaNAs Grown by Gas Source MBE ..... Y. G. Hong</p> <p>2:00 PM Y3 (Student), Deep Levels in GaAs<sub>1-x</sub>N<sub>x</sub> Grown on GaAs by Molecular Beam Epitaxy ..... Ri-an Zhao</p> <p>2:20 PM Y4, Long Wavelength, High Efficiency Photoluminescence from MBE Grown GaInNAsSb ..... Vincent Gambin</p> <p>2:40 PM Y5, The Photoluminescence of Epitaxial InGaNAs for 1.3 Micron GaAs-Based Optoelectronic Devices ..... Jessica MacLean</p> <p>3:00 PM Break</p> <div style="text-align: center; border: 1px solid black; padding: 5px; margin: 5px 0;"> <p><b>Session Z: Epitaxy: Devices</b></p> </div> <p>3:20 PM Z1 (Student), Molecular Beam Epitaxial Growth of InAs Bipolar Transistors ..... Kent L. Averett</p> <p>3:40 PM Z2, Reproducible Growth of AlInAs/InGaAs HBTs by MBE Using a Mathematical Growth-Rate Model ..... B. Shi</p> <p>4:00 PM Z3, Tunable Mid-Infrared Photodetectors Made of In<sub>x</sub>Ga<sub>1-x</sub>As/Al<sub>y</sub>Ga<sub>1-y</sub>As/Al<sub>2</sub>Ga<sub>1-2</sub>As Asymmetric Step Quantum-Well Structure ..... Wengang Wu</p> <p>4:20 PM Z4 (Student), Growth and Properties of AlGaInP Laser Diodes Grown on GaAs and Ge Substrates by Solid Source Molecular Beam Epitaxy ..... Ojin Kwon</p> <p>4:40 PM Z5, Negative Differential Resistance of CdF<sub>2</sub>/CaF<sub>2</sub> Resonant Tunneling Diode Grown on Si(100) Substrate Using Nano area Local Epitaxy ..... Masahiro Watanabe</p>	<p>1:20 PM AA1 (Student), Template-Driven PECVD-Deposited Dielectric Tubules for Nano-Electronic Applications ..... James B. Mattzela</p> <p>1:40 PM AA2 (Student), Selective Molecular Beam Epitaxial Growth of InAs Dots on Nanoscale-Patterned SiO<sub>2</sub>/GaAs(001) ..... S. C. Lee</p> <p>2:00 PM AA3 (Student), Fabrication of Cobalt Silicide/Silicon Nanowires ..... Ahmad M. Mohammad</p> <p>2:20 PM AA4 (Student), Growth Characteristics of Silicon Nanowires Synthesized by Vapor-Liquid-Solid Growth in Nanoporous Membranes ..... Kok-Keong Lew</p> <p>2:40 PM AA5 (Student), Structural and Optical Properties of Vertically Well-Aligned ZnO Nanorods Grown by Metalorganic Vapor Phase Epitaxy ..... W. I. Park</p> <p>3:00 PM Break</p> <p>3:20 PM AA6 (Student), Selective Electric-Field Assembly of Metallic Nanowires ..... Baharak Razavi</p> <p>3:40 PM AA7, Preferred Crystallographic Orientations and Coercivity Mechanism in Self-Ordered Ferromagnetic Nanowires by AC Electroforming ..... W. Y. Lee</p> <p>4:00 PM AA8, Self-Assembled InAs/InP Nanostructures ..... Humberto R. Gutiérrez</p> <p>4:20 PM AA9, Late News</p> <p>4:40 PM AA10, Nanofabrication and Magneto-Characterization of One-Dimensional Quantum Channels in InAs/AlSb ..... C. H. Yang</p>

# 2002 EMC AT-A-GLANCE

Friday Morning June 27, 2002

<b>Session BB: Porous Semiconductors Fabrication, Properties, and Applications</b>	<b>Session CC: Nitride Device Processing: Contacts, Etching, and Dielectrics</b>	<b>Session DD: Biological/Electronic Interfaces</b>
<p>1:20 PM BB1 (Student), Characterization and Effects of Hydrogen Etching of Porous Silicon Carbide ..... Ashutosh Sagar</p> <p>1:40 PM BB2, Array of Macro-Pores on the (100) Plane of N-Type Si Prepared by Photo-Electrochemical Etching ..... Jing-Chie Lin</p> <p>2:00 PM BB3, Effect of Substrate Resistivity on Formation of Porous SiC ..... S. I. Soloviev</p> <p>2:20 PM BB4 (Student), A Comparison of Schottky Diode Performance on Porous and Conventional SiC Substrates ..... Ramya Chandrasekaran</p> <p>2:40 PM BB5 (Student), Design, Fabrication and Characterization of Nanostructured Semiconductor SiC-Based Catalytic Material System ..... J. T. Wolan</p> <p>3:00 PM BB6, Ferromagnetism in Mn Doped Porous GaN: From Clusters to Crystals ..... G. P. Das</p>	<p>8:20 AM CC1 (Student), Thermal Stability of Ti/Al/Mo/Au Ohmic Contacts on N-GaN ..... Deepak Selvanathan</p> <p>8:40 AM CC2 (Student), Improvement of Ohmic Contact on AlGaIn/GaN HEMT Using Inductively Coupled Plasma Etching ..... Derrick Hoy</p> <p>9:00 AM CC3 (Student), Vanadium-Based Contacts to N-AlGaIn and N-AlGaIn/GaN Heterostructures ..... P. K. Wang</p> <p>9:20 AM CC4 (Student), Electric Properties of Ti/Al Ohmic Contacts to Sulfide-Passivated N-GaN ..... June-O Song</p> <p>9:40 AM CC5 (Student), Thermally Stable Capping Technology for Ti/Al Ohmic Contacts to N-GaN ..... Christopher M. Pelto</p> <p>10:00 AM Break</p> <p>10:20 AM CC6 (Student), Electrical Properties of Metal Contacts on KRF Eximer Laser Irradiated GaN ..... Jong Kyu Kim</p> <p>10:40 AM CC7, Transparent Multilayered Schottky Contacts to GaN for Metal-Semiconductor-Metal Photodetectors ..... Dong S. Wu</p> <p>11:00 AM CC8, High-Temperature NH<sub>3</sub> and Low-Temperature Plasma-Assisted N-Atom Surface Cleaning of GaN Prior to GaN-Dielectric Interface Formation for Passivation and Active Layer Formation in Advanced Device Structures ..... C. Bae</p> <p>11:20 AM CC9, Growth and Characterization of Magnesium Oxide Gate Dielectrics on Gallium Nitride ..... Brent Gila</p> <p>11:40 AM CC10 (Student), Smooth, Selective Undercut of (In)GaIn Achieved by Photoelectrochemical Wet Etching ..... Yan Gao</p>	<p>8:20 AM DD1, Silicon and Metal Oxide Biotechnology: New Routes to Catalytic Nanofabrication of High-Performance Materials ..... Daniel Morse</p> <p>8:40 AM DD2 (Student), Investigation and Characterization of Biomolecular Interactions with Inorganic Materials and Surfaces ..... Erin E. Gooch</p> <p>9:00 AM DD3 (Student), Peptide Integration with Conductive Polymers for Nerve Cell Guidance ..... Kiley P. Miller</p> <p>9:20 AM DD4 (Student), Assembly of Quantum Dots by Ribosomal Molecular Machines ..... Ioana Pavel</p> <p>9:40 AM DD5, Late News</p> <p>10:00 AM Break</p> <p>10:20 AM DD6 (Student), Peptide Recognition of Magnetic Materials ..... Brian D. Reiss</p> <p>10:40 AM DD7 (Student), Bacterial Nanosynthesizers: In Vivo Biosynthesis of Cadmium Sulfide Nanocrystals ..... Rozamond Y. Sweeney</p> <p>11:00 AM DD8 (Student), Peptide-Directed Recognition, Nucleation and Control of II-VI Semiconductor Nanomaterials ..... Christine E. Flynn</p> <p>11:20 AM DD9, Building Quantum Dots into Solids with Well-Defined Shapes by Chemical and Biological Routes ..... Chuanbin Mao</p> <p>11:40 AM DD10, Late News</p>

# 2002 EMC AT-A-GLANCE

Friday Morning June 28, 2002

<p align="center"><b>Session EE: Oxide Heteroepitaxy</b></p>	<p align="center"><b>Session GG: Semiconductors: Processing and Oxidation</b></p>	<p align="center"><b>Session HH: Nanostructures</b></p>
<p>8:20 AM EE1, Extended Defects and Misfit Accommodation in Epitaxial <math>\text{Ba}_{0.3}\text{Sr}_{0.7}\text{TiO}_3</math> Thin Films Grown on (001) <math>\text{LaAlO}_3</math> ..... C. J. Lu</p> <p>8:40 AM EE2, Stresses and Defects in Thin-Film Barium-Strontium Titanates—Effects on Ferroelectric Properties ..... Davor Balzar</p> <p>9:00 AM EE3, Intrinsic Bipolar Doping in Transparent Conductive Oxides ..... Xiliang Nie</p> <p>9:20 AM EE4 (Student), Structural Properties of P-MBE ZnO Films on Sapphire with and without MgO Buffer ..... Agus Setiawan</p> <p>9:40 AM EE5, Hetero-Epitaxial Growth of <math>\text{Co}_3\text{O}_4</math> by Low Temperature, Low Pressure MOCVD .....Anil U. Mane</p> <p>10:00 AM Break</p>	<p>8:20 AM GG1 (Student), Chemical and Structural Characterization of GaSb (100) Surfaces Treated by HCl-Based Solutions and Annealed in Vacuum ..... Zhiyan Liu</p> <p>8:40 AM GG2, Effective GaAs Surface Passivation by <math>\text{N}_2\text{-H}_2</math> Remote Plasmas ..... G. Bruno</p> <p>9:00 AM GG3, Low-Frequency Noise Studies of GaAs-On-Insulator MESFETS ..... Susie Tzeng</p> <p>9:20 AM GG4 (Student), Investigation of Digital <math>\text{Al}_x\text{Ga}_{1-x}\text{As}</math> Alloys (<math>x&gt;0.8</math>) for Lateral Oxidation and Regrowth Applications ..... Gregory W. Pickrell</p> <p>9:40 AM GG5 (Student), Selective Dry Etching of GaP Over <math>\text{Al}_{0.6}\text{Ga}_{0.4}\text{P}</math> Using <math>\text{SiCl}_4</math> and <math>\text{SiF}_4</math> ..... John Epple</p> <p>10:00 AM Break</p>	<p>8:20 AM HH1, Temperature Dependent Contactless Electroreflectance Study of Inter-subband Transitions in a Self-Assembled InAs/InP(001) Quantum Dot Structure.....Lyudmila Malikova</p> <p>8:40 AM HH2 (Student), Structural and Optical Characterization of Rapid-Thermal-Annealed InAs/<math>\text{In}_{0.15}\text{Ga}_{0.85}\text{As}</math> DWELL Dots Using X-Ray Diffraction and Photoluminescence ..... Sanjay Krishna</p> <p>9:00 AM HH3, Characterization of InAs Surface Quantum Dots Grown on GaAs by Metalorganic Chemical Vapor Deposition ..... Abdel-Rahman A. El-Emawy</p> <p>9:20 AM HH4, Low-Density Strain-Induced InAs Quantum Dots for Triggered Photon Sources ..... Bingyang Zhang</p> <p>9:40 AM HH5 (Student), Excitonic States in Self-Assembled GaN/AlN Quantum Dots ..... Alexander A. Balandin</p> <p>10:00 AM Break</p>
<p align="center"><b>Session FF: Si-Based Heterojunction Growth and Characterization</b></p> <p>10:20 AM FF1, Comparison of Analytical Techniques for Determining Strain Relaxation and Interdiffusion in Strained Si on Relaxed <math>\text{Si}_{1-x}\text{Ge}_x</math> Heterostructures ..... S. J. Koester</p> <p>10:40 AM FF2 (Student), Strained Germanium P-Type and N-Type MOSFETs Fabricated on <math>\text{Si}_{1-x}\text{Ge}_x/\text{Si}</math> Virtual Substrates ..... Minjoo L. Lee</p> <p>11:00 AM FF3 (Student), The Role of Defects on Heat Conduction in Si and Ge Based Superlattices....Scott Huxtable</p> <p>11:20 AM FF4, Formation of High Quality Silicide on SiGe with High Ge Contents ..... C. V.Y. Lin</p> <p>11:40 AM FF5 (Student), Nickel Silicidation Techniques for Strained <math>\text{Si}_{1-x}\text{Ge}_x/\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y/\text{Si}_{1-y}\text{C}_y</math> Alloys...Z. Shi</p> <p>12:00 PM FF6, Growth of <math>\text{CaF}_2/\text{Si}/\text{CaF}_2</math> Resonant-Tunneling Structures ..... B. H. Mueller</p>	<p>10:20 AM GG6 (Student), Self-Diffusion of Si in Thermally Grown Amorphous <math>\text{SiO}_2</math> ..... Shigeto Fukatsu</p> <p>10:40 AM GG7, Gate Dielectric Formed by Dry Oxidation of Thermal Nitride and its Capability to Prevent Boron Penetration ..... William Wu</p> <p>11:00 AM GG8 (Student), Formation of Shallow Junction Using Spin Coating SPD Method for Sub 0.1 Micron SOI MOSFET ..... Kiju Im</p> <p>11:20 AM GG9, Late News</p> <p>11:40 AM GG10, Late News</p>	<p>10:20 AM HH6, The Influence of the Nominal Thickness of InP Quantum Dots on the Surface Morphology and Structural Properties of InAlP Capping Layers ..... X. B. Zhang</p> <p>10:40 AM HH7 (Student), Ion-Cut-Synthesis of Narrow Gap Nitride Nanostructures ..... Xiaojun Weng</p> <p>11:00 AM HH8, Analysis of Rapid Thermal Annealing of MBE-Grown GaIn(N)As Quantum Wells with GaNAs Barriers ..... Sridhar Govindaraju</p> <p>11:20 AM HH9 (Student), Heteroepitaxial ZnO/ZnMgO Quantum Structures in Nanorods.....W. I. Park</p> <p>11:40 AM HH10, Self-Assembled Growth of Zinc Oxide Nanoislands and Nanorods by Metalorganic Chemical Vapor Deposition .....Shizuo Fujita</p>

# 2002 EMC AT-A-GLANCE

## Friday Afternoon June 28, 2002

Session II: Silicon Carbide: Defects	Session JJ: Wide Bandgap Substrates and Surfaces	Session KK: Non-Destructive Testing and <i>In-Situ</i> Monitoring and Control
<i>Friday Morning, Cont.</i>		
8:20 AM II1, Doping and Temperature Effects on Strain in N-Type 4H-SiC Epilayers ..... Robert S. Okojie	1:20 PM JJ1, Growth of GaN on Electrically Conductive ZrB <sub>2</sub> Substrate by Molecular Beam Epitaxy ..... Jun Suda	1:20 PM KK1 (Student), <i>In Situ</i> Control of Reactive Ion Etching of Patterned Silicon Using Real Time Spectroscopic Ellipsometry ..... Sang-Jun Cho
8:40 AM II2, Stacking Fault Nucleation and Growth in SiC PiN Diodes ..... Robert Stahlbush	1:40 PM JJ2, Properties of Bulk GaN Crystals Grown at High Pressure and High Temperature ..... Mark P. D'Evelyn	1:40 PM KK2, Characterization of the Optical Properties of BeZnTe Thin Films Using Spectroscopic Ellipsometry ..... Frank C. Peiris
9:00 AM II3, Correlation of Bipolar Degradation and Mechanical Stress in 4H-SiC PiN Diodes ..... Jesse B. Tucker	2:00 PM JJ3, Optical Properties of Bulk GaN Crystals Grown from a Na-Ga Melt ..... Brian J. Skromme	2:00 PM KK3, A Combined <i>In-Situ</i> and <i>Ex-Situ</i> Analysis of Hydrogen Radical and Thermal Removal of Native Oxides from (001) GaAs ..... Kurt G. Eyink
9:20 AM II4, Extended Defects Formed During the Forward Bias of 4H SiC PiN Diodes ..... Mark E. Twigg	2:20 PM JJ4, High Purity Semi-Insulating 4H-SiC Substrates for Microwave Device Applications ..... J. R. Jenny	2:20 PM KK4, Micro-Raman Investigation of the N-Dopant Distribution in Lateral Epitaxial Overgrown GaN/Sapphire (0001) ..... Vladimir V. Chaldyshev
9:40 AM II5 (Student), Spontaneous Formation of Stacking Faults in Highly Doped 4H-SiC Wafers During Annealing ..... Thomas Kuhr	2:40 PM JJ5, ZnO Substrates for Optoelectronic Devices ..... Jeff Nause	2:40 PM KK5, Spectroscopic Characterization of Chem-Mechanically Polished and Thermally Annealed N-Type 4H-SiC ..... Bahram Roughani
10:00 AM Break	3:00 PM Break	3:00 PM Break
10:20 AM II6, Processing-Induced Polytype Transformation in Heavily N-Doped 4H-SiC ..... Brian J. Skromme	3:20 PM JJ6, Determination of GaN Polarity by Interaction with H <sub>2</sub> Remote Plasmas ..... Maria Losurdo	3:20 PM KK6 (Student), Cathodoluminescence In-Depth Spectroscopy Study of AlGaN/GaN Heterostructures ..... Fumitaro Ishikawa
10:40 AM II7 (Student), Evidence of Dislocation Nucleation During Homo-Epitaxy of 4H Silicon Carbide ..... Seoyong Ha	3:40 PM JJ7 (Student), Study on Sapphire Surface Preparation for III-Nitride Heteroepitaxial Growth ..... Fransiska Dwikusuma	3:40 PM KK7 (Student), Characterization of the Effects of Device Fabrication on AlGaN/GaN Layers with Spatially Localized LEEN Spectroscopy ..... Gregg H. Jessen
11:00 AM II8, Charge Exchange Among Defects During High Temperature Annealing of 4H High Purity SiC ..... David Alvarez	4:00 PM JJ8, Effect of Chemical Treatment on the Electronic Properties of (0001) GaN Surface ..... Julia W. Hsu	4:00 PM KK8, Advanced X-Ray Scattering and Imaging Techniques for Semiconductor Wafer Characterization ..... Tilo Baumbach
11:20 AM II9, Defect Engineering in SiC: Hydrogen Interaction with Defects and Impurities ..... Yaroslav Koshka	4:20 PM JJ9, Late News	
11:40 AM II10, Late News	4:40 PM JJ10, Late News	

# 2002 EMC AT-A-GLANCE

## Friday Afternoon June 28, 2002

<b>Session LL: Epitaxial Oxides on Silicon</b>	<b>Session MM: Novel Fabrication of Nanostructures</b>	<b>Session NN: Metal Contacts to Semiconductors</b>
<p>1:20 PM LL1 Invited, Silicide/Oxide Heteroepitaxy—A Barrier Offset Study for a Crystalline Dielectric on Silicon ..... Rodney McKee</p> <p>2:00 PM LL2, Epitaxial Silicon-Insulating Metal Oxide Heterostructures ..... Supratik Guha</p> <p>2:20 PM LL3, Atomistic Calculation of Leakage Current Through Ultra-Thin Metal-Oxide Barriers ..... Leonardo R. Fonseca</p> <p>2:40 PM LL4, Epitaxial Growth of Uniformly (100)-Oriented Lanthanum-Substituted Bismuth Titanate Thin Films on Electroded Silicon Substrates ..... Ho Nyung N. Lee</p> <p>3:00 PM Break</p> <p>3:20 PM LL5 (Student), Heteroepitaxial Growth of Conducting Perovskite Oxides on Silicon ..... James Lettieri</p> <p>3:40 PM LL6, Nanoscale Phenomena in Epitaxial Perovskite Oxides on Silicon ..... V. Nagarajan</p> <p>4:00 PM LL7 Invited, Compound Semiconductors on Silicon: A Breakthrough Technology ..... William J. Ooms</p> <p>4:40 PM LL8, Interface Engineering in the Si-SrTiO<sub>3</sub>-GaAs Stack ..... Alex Demkov</p>	<p>1:20 PM MM1 (Student), Ordering of Quantum Dots Using Genetically Engineered Bacteriophage ..... Seung-Wuk Lee</p> <p>1:40 PM MM2, Noble Metal–Peptide Interactions: A Novel Biomediated Route to Metallic Nanoparticles. ..... Daniel J. Solis</p> <p>2:00 PM MM3 (Student), Selective MBE Growth of High Density GaAs/AlGaAs Hexagonal Nanowire Network Structures on Pre-Patterned GaAs Substrates ..... Isao Tamai</p> <p>2:20 PM MM4, Controlled Deposition of II-VI Nanostructures ..... Timo Schallenberg</p> <p>2:40 PM MM5, Sparse Kinked Si Nanowires Growth Catalyzed by TiSi<sub>2</sub> Islands in Gas-Source MBE ..... Qiang Tang</p>	<p>1:20 PM NN1 (Student), Interface Fermi Level Unpinning in Schottky Contacts on N-Type Gallium Arsenide with a Thin Low-Temperature-Grown Cap Layer ..... Saurabh Lodha</p> <p>1:40 PM NN2 (Student), Investigations of Plasma Surface Treatment and its Sequence on the Ohmic Contact on P-GaN ..... Chee Leong Lee</p> <p>2:00 PM NN3 (Student), Phase Diagrams in the Metal-III-Sb Systems for the Design of Contacts to Antimonide Based Compound Semiconductor Devices ..... Wayne Liu</p> <p>2:20 PM NN4 (Student), Design of a Shallow and Thermally Stable Ohmic Contact to P-Type InGaSb ..... Sammy H. Wang</p> <p>2:40 PM NN5, Development of Highly Reliable Schottky in Contacts for CdTe for Radiation Detectors ..... Miki Moriyama</p> <p>3:00 PM Break</p> <p>3:20 PM NN6, Comparison Study of Ohmic Contacts in Oxidizing Ambient at High Temperature for Gas Sensor Applications ..... Sang-Kwon Lee</p> <p>3:40 PM NN7, Nano-Graphitic Flakes and Ohmic Contact Formation on SiC ..... Weijie Lu</p> <p>4:00 PM NN8, Effect of Co or Ni Addition to TiAl Ohmic Contact for P-Type 4H-SiC ..... Osamu Nakatsuka</p> <p>4:20 PM NN9 (Student), Ta/Au Ohmic Contacts to N-ZnO ..... Haifeng Sheng</p> <p>4:40 PM NN10, Morphological Instability of Germanosilicides on Si<sub>1-x</sub>Ge<sub>x</sub> A Comparison Between Ni(Si,Ge) and Ti(Si,Ge)<sub>2</sub> ..... Tobias Jarmar</p>

# 2002 Electronic Materials Conference

## TECHNICAL PROGRAM

Wednesday, June 26, 2002

### EMC PLENARY LECTURE/STUDENT AWARDS

**Ceremony:** 8:20 AM

**Room:** Corwin Pavillion

**Session Chairs:** Ilesanmi Adesida, University of Illinois at Urbana-Champaign, Electrical & Computer Engineering, 319 Micro & Nanotechnology Laboratory, Urbana, IL 61801 USA; April S. Brown, Georgia Institute of Technology, School of Electrical and Computer Engineering, Atlanta, GA 30332-0325 USA

**Plenary Speaker:** David Awschalom, University of California, Santa Barbara, CA

**Topic:** Manipulating Quantum Information with Semiconductor Spintronics

**Break:** 9:20 AM - 10:00 AM

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## Session A: Nitride Epitaxial Growth

Wednesday AM      Room: Lotte Lehmann  
June 26, 2002      Location: University of California

**Session Chairs:** Christian Wetzel, Uniroyal Optoelectronics, 3401 Cragmont Dr., Tampa, FL 33619 USA; Russell D. Dupuis, University of Texas, 10100 Burnett Rd., Austin, TX 78758 USA

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**10:00 AM**

**A1, The Growth and Characterization of High-Quality AlGaIn on Sapphire for Deep UV Emitters:** *Jianping Zhang*<sup>1</sup>; Hongmei Wang<sup>1</sup>; Changqing Chen<sup>1</sup>; Jinwei Yang<sup>1</sup>; Q. Fareed<sup>1</sup>; M. A. Khan<sup>1</sup>; <sup>1</sup>University of South Carolina, Dept. of Electl. Eng., Rm. 3A79, Columbia, SC 29208 USA

Deep ultraviolet (UV) light emitting diodes (LEDs) recently attract extensively interest because of their potential applications in solid-state white light, bio-chemical agent detection and no-line-of-sight communication. The group III nitrides are the highly desirable material system for the solid-state UV LEDs because of their bandgaps ranging from 1.9 eV to 6.2 eV. Several groups using AlGaIn already demonstrated UV LEDs operating at 340-350nm. Our group, on the contrary, using AlGaIn and AlInGaIn recently realized deep UV LEDs with emission wavelengths spanning from 285nm to 340nm with output power exceeding submilliwatt or milliwatt depending on the emission wavelength. It is well recognized that the underlying AlGaIn cladding layers are of extreme importance to get good UV LEDs. Much effort has thus been focused on the growth of AlGaIn on thick, high-quality GaN buffers. Since the use of GaN layers drastically decreases the light extraction efficiency in deep UV emitters due to strong absorption, our group focuses on how to grow high-quality AlGaIn directly on sapphire substrates. Recently we have introduced the AlN/AlGaIn superlattices (SLs) strain-management technique and gotten high quality AlGaIn layers directly on sapphire substrates. In this study, we present the defects filtering effect of the AlN/AlGaIn SLs in the AlGaIn growth. For comparison, AlGaIn layers grown on GaN, AlGaIn layers grown on sapphire with and without AlN/AlGaIn SLs strain-management structure were studied. The samples were analyzed by symmetrical and asymmetrical x-ray diffraction (XRD) mappings, photoluminescence (PL), cathodoluminescence (CL) mapping, chemical etching and the etching pits counted through

atomic force microscopy (AFM) images, and Hall measurements. All these measurements showed that the AlGaIn layers grown on sapphire with the SLs strain-management are of the highest quality. From the (204) asymmetrical mappings, we found the SLs strain-management sample had the smallest width in the asymmetrical w-scan. From the chemical etching, the SLs strain-management sample only had etching pits of 2'108 cm<sup>2</sup>, while the Al<sub>2</sub>Ga<sub>8</sub>N/sapphire and the Al<sub>2</sub>Ga<sub>8</sub>N/GaN samples had etching pits of respectively 1'1010 cm<sup>2</sup> and 8'109 cm<sup>2</sup>. Hall measurements also indicated that the SLs strain-management sample was much superior in electrical properties. Under 3'1018 cm<sup>-2</sup> Si-doping level, the SL strain-management sample had a room temperature mobility of 130 cm<sup>2</sup>/V.s, while the sample Al<sub>2</sub>Ga<sub>8</sub>N/sapphire only had a mobility of 30-60 cm<sup>2</sup>/V.s.

**10:20 AM**

**A2, InGaIn-Channels for Field Effect Transistor Application:** *Matthias Seyboth*<sup>1</sup>; Frank Habel<sup>1</sup>; Ingo Daumiller<sup>2</sup>; Martin Neuburger<sup>2</sup>; Mike Kunze<sup>2</sup>; Erhard Kohn<sup>2</sup>; <sup>1</sup>University of Ulm, Dept. of Optoelect., Ulm 89081 Germany; <sup>2</sup>University of Ulm, Dept. of Elect. Devices & Circuits, Ulm 89081 Germany

Motivation: Comparing III-nitride based devices there is a striking difference between optoelectronic and electronic devices: Whereas most optoelectronic devices make use of the properties of InGaIn/GaN structures electronic devices employ usually AlGaIn/GaN heterostructures. AlGaIn/GaN heterostructure field effect transistors have demonstrated highest microwave power densities and high efficiencies. Unfortunately the polar structure of the III-nitrides enabling this performance also generates charges on the semiconductor surface. These image charges could be identified as a source of large signal RF current compression in a number of GaN-based HFETs. Theory: In case of an InGaIn channel embedded in GaN, both parts of the image charge dipole are located within the channel. For Ga-face material at the GaIn surface the spontaneous polarization image charge is positive as in the AlGaIn/GaN case. At 10% In-content the spontaneous polarizations of the GaIn and InGaIn lattices contribute to only 10% to the interface charges. 90% is generated by piezo polarization due to strain in the InGaIn layer. Since both dipole charges reside in the channel, the FET channel is ambipolar. To obtain an n-type channel, the hole concentration has to be compensated, e.g. by a doping spike in the bottom GaIn barrier layer. With the image polarization channel charge not mirrored at the surface, it is expected that these devices show a reduced large signal RF current compression phenomena. Experimental: Devices revealing promising FET characteristics were realized. To improve understanding of such devices, we examined electronic properties of InGaIn channels. About 20nm thick InGaIn channels covered with approximately 15nm GaIn were grown in an AIXTRON 200/4HT MOCVD system. With a fixed compensation doping, growth temperature and thus In-content was varied from 750 to 830°C and 10 to 25% In, respectively. The accordance of simulated and measured X-ray diffraction patterns, showing good visible Pendelloesung fringes, reveals excellent interface quality. CV-measurements show the transition from under- to overcompensation, when the backside doping spike gets visible. This interdependency of In-content and doping complicates optimization for device structures. Hall data and CV-measurements deliver a coherent picture with sheet carrier densities  $n_s$  around 2E13cm<sup>-2</sup>, mobilities vary from 50 to 350 cm<sup>2</sup>/Vs, dependent on In concentration. However, not completely understood is the saturation behavior where higher saturation currents would be derived from the single channel properties. Channel properties in dependence of channel thickness and compensation doping are under current investigation. Financial support by the Deutsche Forschungsgemeinschaft (DFG) is gratefully acknowledged.

**10:40 AM**

**A3, Intersubband Absorption Observation Ranging the Whole Communication Wavelength ( $\approx$ 1.1-1.6 $\mu$ m) with FWHM of 111-61meV in GaIn/AlIn Multiple Quantum Wells:** *Katsumi Kishino*<sup>1</sup>; A. Kikuchi<sup>1</sup>; H.

Kanazawa<sup>1</sup>; T. Tachibana<sup>1</sup>; <sup>1</sup>Sophia University, 7-1 Kioicho, Chiyodaku, Tokyo 102-8554 Japan

The intersubband transition (ISBT) at the optical communication wavelength ( $\sim 1.3\text{-}1.6\mu\text{m}$ ) can be realized in GaN/AlN multiple quantum well (MQW) structures, because of the large conduction band offset of  $\sim 2\text{eV}$ . Recently, the intersubband absorptions at  $1.3\mu\text{m}$ , and  $1.55\mu\text{m}$  have been measured in GaN/Al(Ga)N-MQWs, grown by molecular beam epitaxy (MBE). In this study, GaN/AlN-MQWs were prepared directly on (0001) sapphire substrates by rf-MBE, to observe the ISBT-absorption at the optical communication wavelength. The MQWs consisted of 90 periods of GaN-well (4-10 mono-layer (ML) in thickness) and AlN barrier ( $\sim 11\text{ML}$ ). ML corresponds to around  $2.6\text{\AA}$ . The ISBT absorption wavelength in the GaN/AlN-MQWs was changed from  $1.14$  to  $1.61\mu\text{m}$  with In the measurement, the one side facet of the samples was irradiated by s- or p-polarized white light, and the transmission light intensity came out from another end through the MQW region, was analyzed by a standard monochromator system. The ISBT absorption occurs only for the light with the electric field polarization, normal to the plane of MQW films (p-polarization). Approximately  $5\text{mm}$  long,  $3\text{mm}$  wide samples, which consisted of  $0.35\text{-}0.45\mu\text{m}$  thick MQWs on  $350\mu\text{m}$  thick sapphire substrates, were prepared. For the light transmission spectra of GaN/AlN-MQW for p-polarized light, clear sharp absorptions were observed at  $1.15$ ,  $1.27$ ,  $1.37$ ,  $1.54$  and  $1.61\mu\text{m}$  in wavelength. The wavelength corresponds to the calculated ISBT wavelength from the first to second subband. The intersubband absorption was demonstrated in the whole communication-wavelength by use of GaN/AlN-MQWs. The full-width at half maximum (FWHM) of the absorption was  $61\text{meV}$  and  $66\text{meV}$  for  $1.54\mu\text{m}$  and  $1.37\mu\text{m}$  samples, respectively, which are the narrowest value among nitride-based ISBT experiments that have been ever reported. FWHM for the  $1.15\mu\text{m}$  sample was  $111\text{meV}$ . For another sample, the ISBT wavelength reached down to  $1.14\mu\text{m}$ , close to a theoretically predicted limitation of  $1.1\mu\text{m}$ . The ISBT wavelengths are explained by flat-band model calculation of GaN/AlN MQW for a thin GaN well range. This experiment shows substantial potentiality of GaN/AlN-MQWs for ISBT-devices developed in the future.

#### 11:00 AM Student

**A4, Electrical and Optical Properties of InN Grown by MBE:** Hai Lu<sup>1</sup>; W. J. Schaff<sup>1</sup>; L. F. Eastman<sup>1</sup>; J. Wu<sup>2</sup>; W. Walukiewicz<sup>2</sup>; K. M. Yu<sup>2</sup>; J. W. Ager, III<sup>2</sup>; E. E. Haller<sup>2</sup>; <sup>1</sup>Cornell University, Dept. of Electl. & Compu. Eng., 427 Phillips Hall, Ithaca, NY 14853 USA; <sup>2</sup>Lawrence Berkeley National Laboratory, Matls. Sci. Div., Berkeley, CA 94720 USA

InN is grown in wurtzite form on either AlN or GaN buffer layers on sapphire. Both buffers are rich in defects due to mismatched growth on sapphire, and the characteristics of InN are partially controlled by these buffers, which are themselves, significantly mismatched to InN. All undoped InN grown are n-type with carrier density more than  $1 \times 10^{18} \text{ cm}^{-3}$ . It is found that for thicker InN films, using AlN or GaN buffer does not result in an apparent difference in the electrical properties of the following InN films, which suggests that lattice mismatch is not a dominant factor limiting the quality of InN epilayers. The high carrier densities would seem to be related to some special defects of InN or impurities. The role of defects may be a source, or compensation, for electrons. A model for Fermi level pinning in the conduction band by dislocations has been developed. Very thin InN layers are compared on the different buffers. Electrical continuity in InN is measured by Hall for layers as thin as  $10\text{nm}$ . Extrapolation of thicker layer electron densities down to zero thickness yields an excess sheet charge density of  $4.3 \times 10^{13} \text{ cm}^{-2}$  for InN on AlN buffers, and  $2.5 \times 10^{13} \text{ cm}^{-2}$  for InN on GaN buffers. This large excess charge must come from either the surface, or the interface between InN and its buffer layer. Since metal contacts, including Ti, Ni and a Hg probe, exhibit no rectification in InN on either of these buffers, it is most likely that at least part of excess charge is located at the surface of InN. Despite high dislocation densities,  $300\text{K}$  mobility beyond  $1300 \text{ cm}^2/\text{Vsec}$  is obtained at  $1.5 \times 10^{18} \text{ cm}^{-3}$ . Most growths have sufficient purity to confirm a recent report that the bandgap of InN is less than half of the widely reported bandgap. Optical absorption, photoreflectance and photoluminescence all show a bandgap of approximately  $0.78\text{eV}$  in all samples.

#### 11:20 AM Student

**A5, Characteristics of GaN Epitaxial Layers Grown on GaN and AlN Buffers by RF Molecular Beam Epitaxy:** Gon Namkoong<sup>1</sup>; W. Alan Doolittle<sup>1</sup>; April S. Brown<sup>1</sup>; Maria Losurdo<sup>2</sup>; M. M. Giangregorio<sup>2</sup>;

Giovanni Bruno<sup>2</sup>; <sup>1</sup>Georgia Institute of Technology, ECE, Sch. of Electl. & Compu. Eng., Atlanta, GA 30332 USA; <sup>2</sup>Istituto di Metodologie Inorganiche e dei Plasmi, IMIP-CNR, via Orabona, 4, Bari 70126 Italy

GaN and related III-V materials have attracted much attention due to their use in short-wavelength optical devices, as well as high-power and high-temperature electronic devices. To date, GaN on sapphire is still of interest due to sapphires' low cost and availability, despite its large lattice mismatch of approximately 16% with GaN. Therefore, the growth initiation process (i.e. nitridation, buffer layer, process conditions, etc.) determines the important characteristics (i.e. polarity, defect densities, and surface morphologies) of the subsequent GaN epitaxial layers. Recently, high temperature (HT) AlN buffer layers have been used to produce Ga-polar GaN epitaxial layers by RF plasma Molecular Beam Epitaxy (MBE). However, it is difficult to obtain high quality AlN buffer layers due to the lower desorption rate and surface diffusion of Al, leading to a three-dimensional (3D) growth. Herein, we investigate the growth conditions for AlN nucleation layers, including the temperature and III/V ratio, and the impact on GaN epitaxial films. The surface reconstruction of AlN on sapphire is monitored by in-situ reflection-high energy electron diffraction (RHEED) to assess the film polarity and infer the surface smoothness. In addition, we present the impact of a new buffer layer: comprised of low temperature GaN on high temperature AlN, on improvement in the structural characteristics of GaN epitaxial layers. AlN buffer layers were grown by adjusting the substrate temperature ( $550\text{-}850^\circ\text{C}$ ) and Al flux ( $1.6\text{-}3.5 \text{ E-7 BEP T}$ ), with constant N flow of  $0.3 \text{ sccm}$ . By monitoring the RHEED, we found that a substrate temperature of  $850^\circ\text{C}$  gives two-dimensional growth, while lower temperatures lead to 3D growth. At this temperature, we observed  $2 \times 2$  reconstruction at  $2.2\text{-}2.5 \text{ E-7 BEP T}$  during the growth which resulted in Ga-polar GaN on the AlN, implying the buffer was Al-polar AlN. However, we observed only a  $1 \times 1$  pattern for the LT GaN buffer. Electric force microscopy measurements (EFM) show lower potential regions that indicate the existence of inversion domains in the GaN epilayer grown on LT GaN buffers. However, we cannot observe lower potential regions of GaN epilayers grown on HT AlN buffer. The structural quality of HT GaN epilayers on AlN buffer layers was characterized by x-ray diffraction (XRD). High quality, non-columnar Ga-polar GaN epilayers with symmetric (0002) and asymmetric (10-4) x-ray rocking curve ( $\dot{\omega}$  scans) of 78 and 248 arcsec can be obtained by a combination of optimized HT AlN buffer, LT GaN buffer and proper annealing conditions. These GaN epilayers show no evidence of inversion domains as investigated by EFM. However, if the proper buffer combinations are not incorporated, the GaN epilayers are grown in a more columnar fashion with asymmetric (10-4) rocking curve FWHMs increasing from 248, 481 to 881 for HT AlN/LT GaN/annealed, HT AlN/LT GaN and HT AlN buffers respectively.

#### 11:40 AM

**A6, Late News**

## Session B: Molecular Electronics

Wednesday AM Room: MultiCultural Theatre  
June 26, 2002 Location: University of California

*Session Chairs:* David Janes, Purdue University, 1285 Elect. Eng. Bldg., W. Lafayette, IN 47906 USA; Theresa Mayer, Pennsylvania State University, 230 Electl. Eng. W., University Park, PA 16802 USA

#### 10:00 AM Student

**B1, Large Area Metal/SAM/Metal Devices by Oblique Evaporation:** Chung-Chen Kuo<sup>1</sup>; Christopher V. Baiocco<sup>2</sup>; Jeremiah K. Mbindyo<sup>3</sup>; Thomas E. Mallouk<sup>3</sup>; Thomas N. Jackson<sup>1</sup>; <sup>1</sup>The Pennsylvania State University, Electl. Eng., 121 EE E. Bldg, University Park, PA 16802 USA; <sup>2</sup>IBM, Semicon. R&D Ctr., B630 1st Floor F3, Hopewell Junction, NY 12533 USA; <sup>3</sup>The Pennsylvania State University, Chem., 152 Davey Lab., University Park, PA 16802 USA

There is increasing interest in electronic devices fabricated using molecular monolayers or a small number of molecular layers. Often such

layers are deposited using self-assembly approaches such as thiol or isonitrile attachment to metals or silane coupling to oxides and with appropriate choice of molecule or molecules these approaches can produce dense, high quality films, often with a high degree of ordering. However, making contacts to molecular devices is often problematic. For metal deposition techniques such as evaporation, incoming metal atoms or clusters can have sufficient mobility to pass through the molecular layer to wet underlying metal (especially when surface energy differences between the molecular layer and underlying metal promote this) and as additional metal is deposited many shorting regions can be formed between top and bottom metal layers. Defects can also play an important role in reducing the yield of molecular devices. Typically molecular layers form with small regions of molecules arranged in ordered arrays with a high degree of perfection. However, the boundaries between ordered arrays are irregular and often have missing molecules and other defects. Such defects can lead to shorts even when reactive chemistry or temperature is used to control adatom-mobility-related shorts. To avoid defect related shorts devices with ultra-small area have been fabricated with the goal of limiting the molecular layer to a single ordered array. We have used a simple approach to reduce or eliminate defect-related shorts in molecular devices. Metal deposition techniques such as evaporation or sputtering are typically arranged so that incoming metal atoms arrive from a direction normal to the sample surface or from a small angle (typically  $< 30^\circ$ ) from normal. To avoid metal shorts, we instead use an oblique deposition technique so that metal atoms arrive at an angle far from normal. This simple technique helps prevent the deposited metal from forming shorts to underlying metal contacts, perhaps because incoming adatom momentum does not favor movement through the molecular layer. The approach can also be combined with reactive chemistry and/or reduced substrate temperature deposition if necessary. Fig. 2 shows the current density as a function of device area for self-assembled monolayers of a simple alkanethiol (mercaptohexadecanoic acid) and for nitrobenzenethiol; the current density uniformity is excellent even for devices with area greater than  $1000 \mu\text{m}^2$ . These results suggest that oblique evaporation may be a useful technique to improve molecular device yield.

#### 10:20 AM Student

**B2, Electrical Contacts to Molecular Layers Using Pre-formed Pads:** *Srinivasan Kadathur*<sup>1</sup>; David Janes<sup>1</sup>; Venugopal Santhanam<sup>2</sup>; Ronald Andres<sup>2</sup>; <sup>1</sup>Purdue University, Sch. of Electl. & Compu. Eng., EE275, 1285 EE Bldg., W. Lafayette, IN 47907-1285 USA; <sup>2</sup>Purdue University, Dept. of Cheml. Eng., W. Lafayette, IN 47907 USA

The electrical properties of molecules have been of considerable interest because of potential applications in molecular electronics. Making good electrical contact to the molecule has been one of the primary problems in such studies. The studies reported to date fall into three general categories of contacts: i) direct probing of molecular layers using scanning tunneling microscopy or conductive atomic force microscopy, ii) metal contacts directly onto a self-assembled monolayer (SAM) of molecules<sup>1</sup>, or iii) pre-formed contacts such as gold nanoclusters, with subsequent probing by scanning probe techniques<sup>2,3</sup>. In order to provide well-understood contacts, it is desirable to extend the pre-formed contact approach to macroscopic structures. In this presentation, we report a macroscopic contact structure in which micron-scale pre-fabricated gold contacts are deposited onto a SAM of molecules, and on electrical characterization studies of various molecules incorporated into these structures. The substrate consisted of a flame annealed 2000Å<sup>0</sup> thick Au film, grown on Si, with a 100Å<sup>0</sup> thick Ti layer for adhesion. A SAM of the desired molecule was then grown on it to complete the bottom portion of the structure. The Au substrate was used as the bottom contact for electrical measurements. For the top-level contact, square Au pads, 4µm x 4µm wide and 4000Å<sup>0</sup> thick, were fabricated using photolithography, on a piece of oxidized silicon. These pads were then "floated-off"<sup>4</sup> by dipping the piece in an extremely dilute solution of HF in water. The pads, which float on the water surface due to surface tension, are then "picked up" on the substrate from the surface of the water. In the case of molecules with top and bottom end groups (e.g. dithiols), soaking the sample in solvent following deposition of the contact pads appears to promote the formation of a chemical bond between the molecule and the top contact pad. We then used an electrical probe to take electrical measurements. The three-probe measurement, a variant of the four-probe measurement technique, allowed us to eliminate the contact resistance of

the bottom contact. The measured low-field resistances correspond to resistances per molecule of 30G ohms for nonanedithiol, 1.5G ohms for XYL and 4000G ohms for DDT. As expected, we find that the aliphatic molecules are more resistive than the aromatic molecules, and that having a chemical bond to both contacts gives more stable and less resistive curves<sup>3</sup>. The resistance values of the aliphatic molecules compare favorably to other studies on the resistance of aliphatic molecules<sup>3</sup>. Encouraged by the initial results, we are currently in the process of trying to make the contact pads smaller and move towards more efficient techniques for the electrical characterization. <sup>1</sup>J. H. Schön et al, Nature 413, 713 (2001); <sup>2</sup>D. Janes et al, Superlattices and Microstructures 18, 275 (1995); <sup>3</sup>X. D. Cui et al, Science 294, 571 (2001); <sup>4</sup>A. Vilan et al, Nature 404, 166 (2000).

#### 10:40 AM Student

**B3, Contact Effects on the Resistance of Molecular Junctions:** *Jeremy M. Beebe*<sup>1</sup>; Vincent B. Engelkes<sup>2</sup>; Larry L. Miller<sup>1</sup>; C. D. Frisbie<sup>2</sup>; <sup>1</sup>University of Minnesota, Chem. Dept., Minneapolis, MN 55455 USA; <sup>2</sup>University of Minnesota, Cheml. Eng./Matls. Sci., 151 Amundson Hall, Minneapolis, MN 55455 USA

Conducting probe atomic force microscopy (CP-AFM) is a useful characterization method for screening molecules that may be of interest in the field of molecular electronics. Using this technique, we measure current-voltage curves for different chain lengths of self-assembled monolayers. Our prior studies have characterized the electron tunneling decay constant,  $\lambda$ , for varying chain lengths of alkanethiols and oligophenylethiols. From these same resistance versus length graphs, we can obtain an effective contact resistance for the junction that depends on the chemistry of the metal-molecule contact. Factors which could affect contact resistance include: the type of metal employed, whether the molecule is physisorbed or chemisorbed to the metal, and the type of chemisorbed contact. In this study, we have determined the contact resistance for junctions formed from alkanethiols, alkyl isocyanides, and alkanedithiols using gold, silver, platinum, and palladium electrodes. Our experimental results show that chemisorbed contacts provide a lower resistance pathway for tunneling than physisorbed contacts, but that the type of chemisorbed contact is immaterial, as both thiol and isocyanide contacts yield similar resistances. In experiments where we have varied the type of metal at the contact, we have observed that the contact resistance changes by orders of magnitude, and that this resistance scales at least roughly with metal work function.

#### 11:00 AM Student

**B4, Electrical Characterization of In-Wire Molecular Electronic Devices:** *James B. Mattzela*<sup>1</sup>; Jeremiah K. Mbindyo<sup>2</sup>; Adriana Zambova<sup>3</sup>; Thomas E. Mallouk<sup>2</sup>; Theresa S. Mayer<sup>3</sup>; <sup>1</sup>Pennsylvania State University, Inter-College Prog. in Matls. Sci. & Eng., University Park, PA 16802 USA; <sup>2</sup>Pennsylvania State University, Dept of Chem., University Park, PA 16802 USA; <sup>3</sup>Pennsylvania State University, Dept. of Electl. Eng., University Park, PA 16802 USA

Research into using molecules as the active component in electronic devices has received much attention in the past several years. Advances in self-assembly and nanotechnology in general have led to the unique synthesis of various molecular devices. Many approaches have been used to create viable test-beds for the electrical characterization of molecules, but few techniques have the capability of being electrically probed macroscopically (by non-atomic force microscopy or scanning tunneling microscopy based techniques). Even fewer of the currently published molecular device structures have the ability of being integrated into more complex circuit designs. The 'In Wire Molecular Device' structure imbeds a self-assembled molecular layer into a metal nanowire of 70nm or smaller diameter. In-wire molecular device structures can then be aligned to test structures or specially designed electronic circuits by various approaches (electro-fluidic, etc.). These devices/circuits can then be electrically characterized by simple macroscopic probing techniques. The synthesis of the in-wire devices is done by first electroplating gold (Au) into a polycarbonate or alumina membrane to create one side of the in-wire molecular device. Molecules with a thiol (sulfur) end group on one side and a carboxylic acid (COOH) group on the other end are then self-assembled into the gold in the membranes by then immersing the membranes into a solution of the molecules of interest. A seed layer is then electrolessly plated on top of the molecular layer by first adsorbing tin (Sn) II; the Sn (II) is then used to create silver (Ag) nanoparticles by rinsing in a solution of AgNO<sub>3</sub>; and finally, Au is electrolessly plated onto



the structure to ensure complete surface coverage. The process is completed by electroplating Au to create the second side of the in-wire molecular device. In-wire molecular devices can then be aligned by an electro-fluidic technique onto the test substrate for macroscopic electrical probing (non-AFM or -STM). Alignment yields of 40% or better can be obtained by this technique. Data on simple insulating alkanethiols shows good match with previously published results. Devices using molecular wires and negative differential resistance (NDR) molecules that were synthesized by this technique have also been characterized and will be discussed in this talk.

11:20 AM

**B5, Rectifying Molecular Diodes from Self-Assembly on Silicon:** *Dominique Vuillaume*<sup>1</sup>; Stephane Lenfant<sup>1</sup>; <sup>1</sup>Institut d'Electronique et Microelectronique du Nord-CNRS, Organic Molecular Matls. & Dev., BP69, Ave. Poincaré, Villeneuve d'Ascq F-59652 Cedex, France

Molecular rectifying diodes have been synthesized based on the Aviram and Ratner paradigm,<sup>1</sup> with donor and acceptor moieties linked by a short  $\sigma$  or even  $\delta$  bridge. This A-b-D group is also substituted by an alkyl chain to allow a monolayer formation by the Langmuir-Blodgett method and sandwiched in a metal/molecule/metal junction.<sup>2,4</sup> Here we report a simplified synthesis using only one donor group and an alkyl chain using a sequential self-assembly process (SAM or self-assembled monolayer). We used a chemical functionalization (by conjugated moieties) of the end-groups of alkyltrichlorosilane SAM's on silicon substrates. Two chemical routes are described and compared: a sequential two-steps method where the alkyl monolayer is first chemisorbed and then the end-groups are functionalized by conjugated moieties, and a direct method, where conjugated molecules substituted by functionalized alkyl spacers are chemisorbed on the surfaces. Alkyl chain lengths are comprised from 6 to 15 methylene units and we used various conjugated groups (phenyl, thiophene, anthracene, pyrene). We characterized the structural properties of these SAM's by FTIR, wettability and ellipsometry. It is shown that densely-packed monolayers are formed. Current rectification is observed for the electronic transport through these Si(n+-type)/ $\delta$ - $\delta$ /metal junctions, with rectification ratio up to the order of 16 and threshold voltages of in the range -0.5 to -0.7 V (voltage applied on a top electrode). The reference sample (the same alkyl chain monolayer without a conjugated group) does not exhibit any rectification behavior. Self-consistent tight binding calculations show that the rectification occurs due to a resonant tunneling transport through the HOMO level of the conjugated group, while the LUMO is too high in energy to be accessible for reasonable applied positive voltages. We show that, for a given conjugated group, the threshold voltage can be slightly tuned by changing the length of the alkyl spacer. Reducing the alkyl length increases the electronic coupling between the conjugated group and the silicon substrate, thus reduces the HOMO-LUMO gap and reduces the threshold voltage. These results confirm our previous theoretical analysis<sup>5</sup> that rectification in the metal/C16H33-Q-3CNQ/metal junction<sup>2,4</sup> is not due to the AR mechanism but simply that any conjugated molecule with a sufficient alkyl spacer from one of the electrode in a metal/molecule/metal junction can behave as a molecular rectifying diode. <sup>1</sup>A. Aviram and M. A. Ratner, Chem. Phys. Lett. 29, 277-283 (1974); <sup>2</sup>R. M. Metzger, B. Chen, U. Höpfner, M. V. Lakshmikantham, D. Vuillaume, T. Kawai, X. Wu, H. Tachibana, T. V. Hughes, H. Sakurai, J. W. Baldwin, C. Hosch, M. P. Cava, L. Brehmer, and G. J. Ashwell, J. Am. Chem. Soc. 119, 10455-10466 (1997); <sup>3</sup>R. M. Metzger, T. Xu, and I. R. Peterson, J. Phys. Chem. B 105, 7280-7290 (2001); <sup>4</sup>D. Vuillaume, B. Chen, and R. M. Metzger, Langmuir 15, 4011-4017 (1999); <sup>5</sup>C. Krzeminski, G. Allan, C. Delerue, D. Vuillaume, and R. M. Metzger, Phys. Rev. B 64, 085405 (2001).

11:40 AM

**B6, A Nanostructured Gas Sensor: Coupling a Selective Molecular Level Event to an External Circuit:** *Jaewon Choi*<sup>1</sup>; David B. Janes<sup>1</sup>; Venugopal Santhanam<sup>2</sup>; Rajan Agarwal<sup>2</sup>; Ronald P. Andres<sup>2</sup>; <sup>1</sup>Purdue University, Electl. & Compu. Eng., Box 170, 1285 EE Bldg., W. Lafayette, IN 47907-1285 USA; <sup>2</sup>Purdue University, Cheml. Eng., 1283 Cheml. Eng. Bldg., W. Lafayette, IN 47907-1283 USA

There have been numerous studies of molecules as electrical wires. These studies generally utilize adsorption of molecules onto a metal surface to form a self-assembled monolayer (SAM). Most studies of such SAMs have been done with n-alkyl thiols on Au(111) surfaces. The electrical contact to the SAM is achieved by means of a sharp probe or a metal film deposited on top of the SAM. However, in order to couple to

macroscopic contacts as well as to provide an open surface for interactions such as gas sensing, it is advantageous to utilize a network of molecularly-linked metal nanoclusters that bridge the gap between metal electrodes on an insulating surface. In these structures, the electrical conductance of the linked cluster network is determined by the resistance of the intercluster linking molecule, with contributions from the capacitive charging in the network. By incorporating molecular linkers with highly specific binding properties for selected gases, it should be possible to make a very sensitive and highly selective sensor with direct electrical readout. In this paper, we describe progress toward realizing a new type of gas sensor with direct electrical readout using a Au nanocluster array with selective molecular linkers. The macroscopic contact pads consisted of interdigitated Au finger patterns with various spacings formed on a SiO<sub>2</sub> surface with conventional UV lithography, e-beam evaporation, and liftoff. To enhance the contact continuity between the cluster film and the Au fingers, thin metallization (10 nm) was used. Thicker Au layers were used on the probe pads for stable probing. High quality monolayer arrays of 5nm diameter or 10nm diameter Au clusters, that are encapsulated by alkanethiol molecules, were formed on a water surface and picked up by a flat elastomeric pad of polydimethylsiloxane. The arrays were subsequently transferred to the contact pad structures by stamping. The procedure was repeated a second time in order to form a cluster bilayer on the substrate. A bilayer provides a more flexible structure for intercluster linking. For a typical bilayer film of 5nm diameter clusters, the sheet resistance of  $\sim 10^9 \Omega/\mu\text{m}$  and the contact resistance between the film and the Au fingers of  $\sim 10^9 \Omega/\mu\text{m}$  were measured. These results establish that the resistance is not dominated by the contact resistance to the Au fingers, indicating that a modulation of the sheet resistance by docking of gas molecules will be observable. We are currently in the process of inserting porphyrin molecules as intercluster linkers. It is expected that the substitution of various metal atoms in the porphyrins will provide selective docking, and therefore selective recognition of various gas species. This structure has the potential to provide selective and highly sensitive gas sensing, and can be easily integrated with CMOS control circuitry.

## Session C: Nanoscale Characterization

Wednesday AM Room: UCEN State Street  
June 26, 2002 Location: University of California

*Session Chairs:* Edward Yu, University of California-San Diego, ECE Dept., MC 0407, La Jolla, CA 92093 USA;  
Rachel S. Goldman, University of Michigan, Dept. of MSE, Ann Arbor, MI 48109-2136 USA

10:00 AM

**C1, Two-Photon Laser Scanning Microscope for UV Spectroscopy and Lithography:** Frederik Schrey<sup>1</sup>; Ed Chaban<sup>1</sup>; *Julia W. Hsu*<sup>1</sup>; <sup>1</sup>Lucent Technologies, Bell Labs., 600 Mountain Ave., Murray Hill, NJ 07974 USA

A two-photon laser scanning microscope (TP-LSM) optimized for spectroscopy of GaN and for three-dimensional photolithography was built. The light source is a femtosecond Ti:sapphire laser pumped by a doubled YAG laser. The Ti:sapphire laser was optimized for higher output at short wavelength, i.e. 700nm. The beam was expanded and collimated to cover the back aperture of the objective. The selection of microscope objective is critical. High numerical aperture (NA) is desired for high resolution. However, the transmission of most high NA objectives starts to diminish near 360nm and will distort the near-bandgap emission spectra from GaN. We use a LUM Plan FL 60x (0.9 NA) water immersion objective from Olympus. The fundamental laser light and the luminescence produced by two-photon absorption of GaN is separated using a dichroic beam splitter. The collected light is dispersed by a SPEX 270M spectrometer and detected using either a charge couple device or a photomultiplier tube. To form an image, the sample is rastered using a piezo scanner while all optical components and the laser beam remain stationary. The lateral resolution of our TP-LSM is  $\gg 0.6 \mu\text{m}$  for the fundamental wavelength and  $\gg 0.3 \mu\text{m}$  for the second harmonic. We used

this TP-LSM to study the spatial variation of photoluminescence (PL) in bulk GaN films as well as lateral epitaxially overgrown (LEO) structures. We find that the excitation intensity dependence for the near bandgap emission (NBE) is quadratic while that for the sub-bandgap defect luminescence is linear. Furthermore, we find nanometer scale variation of NBE while the yellow luminescence is more uniform. In LEO films, depending on the PL wavelength monitored, the spatial distribution varies, indicating inhomogeneous distribution of defects and impurities. The TP-LSM can also be used in direct photopolymerization of UV absorption polymers. The advantages over conventional lithography are higher resolution and the capability to fabricate three-dimensional structures.

#### 10:20 AM Student

**C2, Cross-Sectional Scanning Tunneling Microscopy Studies of Phase Separation in InP/GaP Short Period Superlattices:** *Byungha Shin*<sup>1</sup>; Wenzhou Chen<sup>1</sup>; Rachel S. Goldman<sup>1</sup>; Jin D. Song<sup>2</sup>; Jong M. Kim<sup>2</sup>; Yong T. Lee<sup>2</sup>; <sup>1</sup>University of Michigan, Matls. Sci. & Eng., 2300 Hayward St., Ann Arbor, MI 48109-2136 USA; <sup>2</sup>Kwangju Institute of Science and Technology, Info. & Comm., Oryong-dong, Kwangju 506-712 Korea

During the past decade, spontaneous lateral phase separation, often referred to strain induced lateral ordering (SILO) or lateral composition modulation (LCM), has been reported in short period superlattices (SPS) consisting of alternating a few monolayers (ML) of binary compounds with nearly equal and opposite misfit with respect to the substrate. Formation of this lateral phase separation in the presence of SPS provides an opportunity to synthesize low dimensional structures such as quantum wires without further post-growth processing. Knowledge of the evolution of the lateral phase separation and its impact on local heterojunction band offsets is of critical importance for future device design. In this work, we have used ultra-high vacuum cross-sectional scanning tunneling microscopy (XSTM) to examine the evolution of lateral phase separation and local heterojunction band offsets within InP/GaP SPS. The structures consisted of alternating InP and GaP layers grown on GaAs by molecular beam epitaxy. XSTM reveals the presence of lateral contrast modulations, presumably due to a combination of compositional and strain variations within the SPS. The modulations, with wavelengths ranging from 5 to 15nm, were apparently initiated at the onset of the SPS growth. Interestingly, the amplitude of the contrast modulations is significantly lower than that observed in phase-separated InAlAs alloys<sup>1</sup>. Furthermore, filled state XSTM images of the SPS/GaAs interface suggest a negligible valence band offset between one of the phase-separated constituents and GaAs. We will discuss the relative contributions of compositional and strain variations to the observed modulations, as well as their impact on the conduction and valence band offsets. This work was supported in part by the NSF (CAREER Award) and the Army Research Office (MURI Program). <sup>1</sup>B. Shin, A. Lin, K. Lappo, R. S. Goldman, M. C. Hanna, S. Francoeur, A. G. Norman, and A. Mascarenhas, submitted (2002).

#### 10:40 AM Student

**C3, Variation of Interface Structure in InGaAs/InP Heterostructures Studied by Scanning Tunneling Microscopy:** *H. A. McKay*<sup>1</sup>; R. M. Feenstra<sup>1</sup>; P. J. Poole<sup>2</sup>; G. C. Aers<sup>2</sup>; <sup>1</sup>Carnegie Mellon University, Dept. of Physics, Pittsburgh, PA 15213 USA; <sup>2</sup>National Research Council of Canada, Inst. for Microstruct. Scis., Ottawa K1A0R6 Canada

InGaAs/InP heterostructures have important applications in optical detectors; modulators and quantum well laser structures. The operation of such devices may depend on the interface properties, and in particular, on possible asymmetry between interfaces of InGaAs grown on InP and InP grown on InGaAs interfaces. It is known that exchange of anion species can play a significant role for both types of interfaces, and furthermore, that carryover of As from the InGaAs wills into the InP barrier also occurs. In this work, cross-sectional scanning tunneling microscopy (XSTM) was used to study the (110) cleaved surface of a multiple quantum well (MQW) system grown by chemical beam epitaxy. Four different gas switching sequences were used in the MQW structures, and the consequences of the switching sequence are readily apparent in the XSTM images. Strain in the MQW leads to a distortion of the nominally flat cleavage surface, which is accurately measured by STM and is compared with finite element simulations for specific MQW compositional profiles. We find that when growing lattice matched InGaAs on InP, a thin compressively strained layer is always present at the interface, arising from exchange of As and P in the InP region near the interface. The specific gas switching sequences used are found to have only small impact on the

composition of this layer. For growth of InP on InGaAs, exchange of As and P leads to a tensilely strained interface layer. In this case, however, the composition of this layer can be significantly changed by varying the switching sequence. In particular, performing a P soak of the InGaAs prior to InP growth (as used by some workers for short period superlattice studies) produces more exchange and concomitantly larger strain in the interface region. Greater carryover of As into the InP is also predicted in this case. In addition, alloy clustering has been studied in the InGaAs/InP MQWs and thicker alloy layers. Various samples (as-grown, ion implanted, or thermally annealed) were studied to observe possible effects of cation clustering. Using autocorrelation analysis and finite element simulations of the STM images, it was found that the arrangement of In/Ga atoms is consistent with a random distribution in all the systems studied.

#### 11:00 AM Student

**C4, Indium-Indium Pair Correlations Within the Wetting Layers of Buried InAs/GaAs Quantum Dots:** *Byungha Shin*<sup>1</sup>; Bogdan Lita<sup>1</sup>; Jamie D. Phillips<sup>2</sup>; Pallab K. Bhattacharya<sup>2</sup>; Rachel S. Goldman<sup>1</sup>; <sup>1</sup>University of Michigan, Matls. Sci. & Eng., 2300 Hayward St., Ann Arbor, MI 48109-2136 USA; <sup>2</sup>University of Michigan, Electl. Eng. & Compu. Sci., 1301 Beal Ave., Ann Arbor, MI 48109-2122 USA

Recently, arrays of stacked quantum dots have shown significant promise for a variety of novel device applications. In the InAs/GaAs system, the regions between the InAs islands, often termed the "wetting layers", contain a few layers of sparsely populated In atoms within a GaAs matrix. Detailed studies of the interactions and dynamics of In atoms in the wetting layers are very important for device applications of self-assembled InAs/GaAs quantum dots. For example, the dark current in quantum dot-based infrared detectors may be suppressed by eliminating the wetting layer while retaining the vertical and lateral separation of dots within a quantum dot superlattice structure. Furthermore, in the past few years, several theoretical and experimental efforts have elucidated non-randomness phenomena such as clustering and segregation in dilute alloys of compound semiconductors. These issues are just beginning to be explored in non-dilute alloys far beyond the percolation limit, such as the wetting layers of buried InAs/GaAs quantum dots. For example, we recently reported the first direct measurements of In-Ga interdiffusion and In surface segregation lengths, within the wetting layers of buried InAs/GaAs quantum dots<sup>1</sup>. Here, we report cross-sectional scanning tunneling microscopy (XSTM) studies of In-In pair correlations within the wetting layers. In many high resolution XSTM images, we counted the number of In-In pairs along the [110] direction as a function of the spacing between them. Since the number of In-In pairs greatly exceeds that for a randomly generated distribution of In atoms, significant lateral In clustering within the wetting layers is apparent. In order to deduce an In-In pair interaction energy, we compared the experimentally determined and randomly generated In-In pair distributions. Interestingly, the nearest neighbor In-In interaction energies are similar to those previously calculated for the unreconstructed dilute InGaAs alloy surface<sup>2</sup>. This suggests that lateral In clustering along the InAs wetting layer may be frozen in during growth, and that the wetting layer might provide a fast diffusion path for annealing-induced ordering of quantum dot arrays. In addition, a comparison of In short range segregation parameters before and after high temperature annealing suggests that the In atoms may prefer to diffuse together. This work was supported in part by the Army Research Office (MURI Program). <sup>1</sup>B. Lita, R. S. Goldman, J. D. Phillips, and P. K. Bhattacharya, Appl. Phys. Lett. 75, 2797 (1999); Surf. Rev. Lett. 5, 539 (2000); <sup>2</sup>J.-H. Cho, S. B. Zhang, and A. Zunger, Phys. Rev. Lett. 84, 3654, (2000).

#### 11:20 AM Student

**C5, Nano-Faceting of the GaAs(311) Surface:** *Vahid Yazdanpanah*<sup>1</sup>; Zhiming Wang<sup>1</sup>; Gregory J. Salamo<sup>1</sup>; <sup>1</sup>University of Arkansas, MRSC & Microelect. Photonics, Fayetteville, AR 72701 USA

High index GaAs surfaces have been the subject of much recent attention for several reasons. First, they play a key role in determining the shape of the growth of nanostructures. Second, they provide unique templates for further nanostructure growth. Third, high index surfaces with high energies can spontaneously turn into other surfaces with lower energies, on which nanostructures can be directly synthesized. For this investigation, double sided polished GaAs(311) substrates were used for a comparative study of the growth on the GaAs(311)A and B surfaces in an ultra-high vacuum combined molecular beam epitaxy (MBE)/scan-

ning tunneling microscopy (STM) facility. It was found that the GaAs(311)A and B surfaces are both faceted into (110) and (111) surfaces on a nano-scale. In-situ RHEED indicates that the GaAs(311)A surface is kinetically limited to a scale of about 2nm, with 1.2nm in the (110) plane and 0.8nm in the (111) plane. During a growth interruption, however, the faceted GaAs(311)A surface was observed to transform to a larger scale, indicated by the appearance of RHEED streaks reflected from the (110) and the (111) surfaces. Specifically, STM images reveal ordered ribbons along the [-110] direction with a lateral spacing of 7nm after a 5 minute growth interruption at 580C. However, the growth of the GaAs(311)A surface at 500C can also be quickly quenched to room temperature while maintaining the RHEED pattern and surface ribbons with a period of around 2nm. The faceted surfaces in both cases were confirmed by our atomic resolution STM images. Similar nano-faceted behavior was also observed, via both RHEED and STM images, on the GaAs(311)B surface. To our knowledge, this is the first reported observation of a nano-faceted high index compound semiconductor surface in real space. One application of the nano-faceting of the GaAs(311) surfaces observed here is that it can provide a unique and controllable way to grow uniform quantum wire structures. The resulting unique electrical and optical characteristics are currently under study.

11:40 AM

**C6, Compositional Analysis of Graded  $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$  Layers by X-Ray Energy Dispersive Spectrometry:** *Krishnamurthy Mahalingam*<sup>1</sup>; Robert Wheeler<sup>1</sup>; Kurt G. Eyink<sup>1</sup>; Steven T. Fenstermaker<sup>1</sup>; James S. Solomon<sup>1</sup>; <sup>1</sup>Air Force Research Laboratory, AFRL/MLPSO, Bldg. 651, Wright-Patterson AFB, OH 45433 USA; <sup>2</sup>Air Force Research Laboratory, AFRL/MLLN, Bldg. 655, Wright-Patterson AFB, OH 45433 USA

Compositionally graded  $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$  layers are important materials for graded-index wave guide applications, wherein the index of refraction varies continuously with Al content. Successful application of these materials requires characterization techniques that can accurately quantify both, the shape of the graded profile and its composition. The use of techniques such as SIMS and Auger electron spectroscopy (AES) pose problems due to insufficient spatial resolution and inaccuracies in composition due to smearing from adjacent layers. In this study we employ the X-ray energy dispersive spectrometry (XEDS) technique to characterize a variety of  $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$  layers with linear, parabolic and sinusoidal grading in the Al content. The individual layers were grown by molecular beam epitaxy, with film thickness and composition monitored in-situ by spectroscopic ellipsometry (SE). The XEDS measurements were obtained using field emission gun transmission electron microscope (FEG TEM), to exploit the small probe size (high spatial resolution) and high brightness (improved sensitivity) associated with the FEG source. The Al/Ga composition profiles were determined based on the Cliff-Lorimer (CL) equations, assuming the thin-foil criterion. The so called "k-factors" in the CL equations ( $k_{\text{Al-As}}$ ,  $k_{\text{Ga-As}}$  and  $k_{\text{Al-Ga}}$ ), required for calculating the composition profiles, were determined from precalibrated  $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$  layers. Further details on the comparison between XEDS results with those obtained from other techniques will be presented. The application of XEDS to identify film growth related problems, such as flux transients, will also be discussed.

## Session D: Antimonide-Based Materials & Devices - I

Wednesday AM Room: UCEN Harbor  
June 26, 2002 Location: University of California

*Session Chairs:* Ralph Dawson, University of New Mexico, EECE Dept., 1313 Goddard SE, Albuquerque, NM 87106 USA; Andrew Johnson, QinetiQ, Ltd., UK

10:00 AM

**D1, Growth of GaAsSb/GaAs Double Quantum Well Lasers Emitting Near 1.3  $\mu\text{m}$ :** *Irene C. Ecker*<sup>1</sup>; Susanne Menzel<sup>1</sup>; Juergen Joos<sup>1</sup>; Ihab Kardosh<sup>1</sup>; Rainer Michalzik<sup>1</sup>; Karl J. Ebeling<sup>2</sup>; <sup>1</sup>University of Ulm, Optoelect., Albert-Einstein-Allee 45, Ulm 89081 Germany; <sup>2</sup>Infineon Technologies AG, Rsrch., Otto-Hahn-Ring 6, Muenchen 81730 Germany

In fiber-optic communication systems, light emitting devices at 1.3  $\mu\text{m}$  are widely used. As cost-effective sources for, e.g., metro access networks, manufacturable vertical-cavity surface-emitting laser diodes (VCSELs) with a corresponding emission wavelength are highly desirable. GaAs based devices might prove superior to their InGaAsP counterparts in aspects like thermal stability, single epitaxial growth capability, and use of large diameter high-quality inexpensive GaAs substrates. Until now various approaches to VCSEL structures have been investigated. These concentrate mainly on InAs/InGaAs quantum dots, GaInNAs and GaAsSb quantum films. As an intermediate step towards 1.3  $\mu\text{m}$  VCSELs, in this paper we present results on the growth of GaAsSb/GaAs edge-emitting laser diodes. Growth of Edge-Emitting Laser Diodes: The epitaxial layers were grown with both, the group V precursor arsine and solid arsenic. For antimony a solid source is used. The laser active region of the investigated edge emitting laser diodes consists of two 7nm thick compressively strained GaAsSb quantum wells and a 30nm thick GaAs barrier. The double quantum well structure is surrounded by GaAs with a thickness of 40nm. The active region is embedded in carbon and silicon doped AlGaAs cladding layers. Device Characteristics: We report on the characterization of GaAsSb/GaAs broad area laser diodes with as-cleaved facets under continuous wave (cw) and pulsed operation without heat sinking at room temperature. The cw output characteristics of a device with 800  $\mu\text{m}$  length and 20  $\mu\text{m}$  shows a threshold current density as low as 357 A/cm<sup>2</sup> for a center wavelength exceeding 1160nm. The temperature dependence of the threshold current density is measured within a range of 283 to 296K, yielding a characteristic temperature  $T_0 = 68\text{K}$ . This value is comparable to published GaAsSb and InGaAsP laser data and is attributed to the weak electron confinement in the GaAsSb quantum wells. The light-current characteristic of a 800 x 20  $\mu\text{m}^2$  device with emission near 1.3  $\mu\text{m}$  is determined under pulsed conditions (pulse length = 50 ns and repetition rate = 1 kHz). The threshold current density is 2.2 kA/cm<sup>2</sup>. Laser oscillation is observed at about 1294nm wavelength. The results attained so far for the active material are currently being transferred to surface-emitting devices. Presently, edge-emitting laser diodes processed from wafers with VCSEL-type layer structures show laser operation at about 1.2  $\mu\text{m}$  with threshold current densities of 940 A/cm<sup>2</sup> which are higher than reported above due to reduced optical confinement. Optimized DBR doping profiles and increased round-trip gain through multiple quantum wells have been identified as key improvements necessary to achieve VCSEL operation in the future.

10:20 AM Student

**D2, Characterization of Effects of Various Barrier Materials on GaAsSb 1.3 $\mu\text{m}$  QW Heterostructures Grown by Metalorganic Chemical Vapor Deposition:** *Min S. Noh*<sup>1</sup>; Jae H. Ryou<sup>1</sup>; Ying L. Chang<sup>2</sup>; Robert Weissman<sup>3</sup>; Russell Dupuis<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Electl. & Compu. Eng., Microelect. Rsrch. Ctr., Austin, TX 78712 USA; <sup>2</sup>Agilent Technologies, Inc., Agilent Labs., 3500 Deer Creek Rd., Palo Alto, CA 94304 USA; <sup>3</sup>Agilent Technologies, Inc., 370 Trimble Rd., San Jose, CA 95131 USA

Long-wavelength semiconductor laser diodes emitting at  $\sim 1.3\mu\text{m}$  and 1.5 $\mu\text{m}$  are recognized as the most important optoelectronic devices because of the possibility of high-bit-rate and loss-free long distance optical fiber communications. Recently, Vertical Cavity Surface Emitting Lasers (VCSELs) operating at 1.3 $\mu\text{m}$  and grown on GaAs substrates have been attracting great interest for high-performance, low-cost communication system applications. For the QW actives which give 1.3 $\mu\text{m}$  emission, several materials like InGaAsN and In(Ga)As QD have been investigated intensively. GaAsSb materials have been studied for this application too. Strain-controlled GaAsSb QW heterostructures grown on GaAs substrates can be good candidates for this purpose in spite of the large lattice mismatch ( $\sim 2.7\%$ ) for GaAsSb<sub>0.35</sub>/GaAs, the wide range of miscibility gap (0.2 $\sim$ Sb $\sim$ 0.8) expected for typical growth conditions, and the expected Type-II band alignment of the GaAsSb/GaAs heterojunction. To overcome this immiscibility problem, GaAsSb layers were grown using metastable conditions at low growth temperature and high growth rate. In order to improve the electrical confinement, which gives better device performances such as higher characteristic temperature ( $T_0$ ), higher efficiency, and higher output power, a Type-I band alignment is preferable to that of Type-II. Also strain-compensated (SC) QW heterostructures lead to another way to improve the luminescence property. Due to the high strain effect of GaAsSb grown on GaAs, the growth of thicker layer QW or multiple-QW active region structures is restricted. It is possible to

increase the critical thickness by introducing SC layers near the QW. Of primary importance is the band alignment between the quantum-well and the barrier material. In this work, we have grown GaAsSb double-quantum-well separate-confinement heterostructures (DQW-SCHs) with various barrier materials to investigate the band alignment between the barrier and the GaAsSb QW. MQW structures were also grown. We report the evidence of Type-I emission with various GaAsSb quantum-wells with different barrier materials. Type-I band alignment was verified by using low-temperature cathodoluminescence (CL) and photoluminescence (PL) measurements. Heterostructures having a strain-compensated Type-I band alignment exhibit strong 300K PL emission at wavelengths of 1.3 $\mu$ m. Our earlier GaAsSb injection lasers employed Type-II heterostructures. Devices employing this new Type-I active region structure are under investigation and injection laser results will be described.

#### 10:40 AM Student

**D3, MBE Growth and Device Performance of GaAsSb Resonant-Cavity-Enhanced Avalanche Photodiodes with Separate Absorption, Charge and Multiplication Regions:** X. Sun<sup>1</sup>; S. Wang<sup>1</sup>; R. Sidhu<sup>1</sup>; X. G. Zheng<sup>1</sup>; X. Li<sup>1</sup>; J. C. Campbell<sup>1</sup>; A. L. Holmes, Jr.<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Electl. & Compu. Eng., 10100 Burnet Rd., Austin, TX 78758 USA

We have demonstrated, for the first time, a 1.31 $\mu$ m GaAsSb resonant-cavity-enhanced (RCE) separate absorption, charge and multiplication (SACM) avalanche photodiode (APD) on a GaAs substrate. The material was grown in a Varian Gen II solid source MBE system. Our experiments showed that the growth of GaAs<sub>1-x</sub>Sb<sub>x</sub> depends on the growth temperature, Ga growth rate, group-V beam equivalent pressures (BEPs) and their ratio. The optimized growth temperature of GaAsSb on GaAs substrate is 510~530°C and the Ga growth rate is 0.8~1.0 ml/s. For 1.31 $\mu$ m emission, As BEP of 2.5 x 10<sup>-6</sup> Torr and Sb BEP of 5.0 x 10<sup>-7</sup> Torr were used during the growth of GaAsSb layers. Measured and simulated X-ray diffraction spectra showed that the Sb mole fraction was approximately 0.35 in these GaAs<sub>1-x</sub>Sb<sub>x</sub> layers. In order to obtain higher quantum efficiency from these very thin absorption layers, a 2 $\bar{e}$  resonant cavity with a GaAs/AlAs bottom DBR mirror and a MgF<sub>2</sub>/ZnSe dielectric top mirror was utilized. In order to minimize the compressive strain in the GaAsSb layers, the absorption region consisted of four 150Å thick undoped GaAs layers sandwiched between five 56Å thick undoped GaAsSb layers. Two such absorption regions were placed at the antinodes of the optical standing wave inside the cavity to increase the quantum efficiency of the detector. The separation of GaAsSb absorption regions and undoped Al<sub>0.9</sub>Ga<sub>0.1</sub>As multiplication region effectively reduced the multiplication and band-to-band tunneling in the narrow-bandgap GaAsSb layers and thus significantly lowered down the dark current in this device. A thin lightly p-doped Al<sub>0.9</sub>Ga<sub>0.1</sub>As "charge" layer between the absorption and multiplication regions ensured a low field in the absorption region. For this device, the breakdown occurred at 24V and a DC gain up to 40 was obtained near breakdown. At 90% of the breakdown, the dark current was approximately 5nA, which was 1000 times lower than the dark current of a GaAsSb RCE *p-i-n* photodiode we previously reported. For the device with 2 pairs of  $\bar{e}/4$  MgF<sub>2</sub>/ZnSe layers as the dielectric top mirror, the peak external quantum efficiency was 36% at the wavelength of 1.31 $\mu$ m and the full width at half maximum (FWHM) was 7nm. From our previous results and simulation, the external quantum efficiency should be approximately 50%. We will talk about this in the presentation. Our work on this GaAsSb RCE SACM avalanche photodiode shows that GaAsSb is a promising material for 1.3 $\mu$ m photodetectors on GaAs substrates.

#### 11:00 AM Student

**D4, Optically Pumped AlGaInSb/GaInSb Multiple Quantum Well Lasers:** Edwin Pease<sup>1</sup>; L. R. Dawson<sup>1</sup>; Leslie G. Vaughn<sup>1</sup>; Luke F. Lester<sup>1</sup>; <sup>1</sup>University of New Mexico, Ctr. for High Tech. Matls., 1313 Goddard SE, Albuquerque, NM 87106 USA

High power, low threshold lasers using InGa(As)Sb Type-I quantum wells with emission wavelengths of 2  $\mu$ m have been demonstrated. However, to extend the wavelength from 2  $\mu$ m toward 3  $\mu$ m, increased As content has been needed to alter the bandgap and maintain a lattice match to GaSb resulting in degraded performance. In this work, the need for lattice match between the active region and the GaSb substrate is avoided by the use of metamorphic AlInSb superlattice buffer layers, which provide a low defect density substrate tailored to the desired lattice constant. Thus, the need for arsenic is completely eliminating. With increased arsenic there is a loss of valence band offset losing 2-D confinement of

the holes in the quantum wells. The relaxation of the buffer layer generates defects that may propagate into the active region through threading dislocations. Surface defects can be visible seen in the form of cross-hatching and rosettes. AlInSb metamorphic buffers with larger than 40% indium content show crosshatching visible without Nomarski microscopy and a marked decrease in photoluminescence. Using these buffer layers, we report optically pumped arsenic-free lasers with emission as long as 3.3  $\mu$ m on buffers terminating with Al<sub>0.46</sub>In<sub>0.54</sub>Sb. Threshold and efficiency are substantially increased with increased compressive strain in the quantum well. One laser with a metamorphic buffer terminating in Al<sub>0.73</sub>In<sub>0.27</sub>Sb using AlGaInSb barriers and Ga<sub>0.6</sub>In<sub>0.4</sub>Sb quantum wells, producing laser emission under optical pumping at 2.5  $\mu$ m at room temperature with a threshold current density of 946 W/cm<sup>2</sup> and a quantum efficiency of 15%. A second laser with a buffer terminating in Al<sub>0.64</sub>In<sub>0.36</sub>Sb, with AlGaInSb barriers and Ga<sub>0.4</sub>In<sub>0.6</sub>Sb quantum wells, producing laser emission at 2.8  $\mu$ m at room temperature with a threshold current density of 360 W/cm<sup>2</sup> and a quantum efficiency of 28%.

#### 11:20 AM

**D5, Physics of Sb-Heterostructure Quantum Tunneling Millimeter Wave Diodes:** J. N. Schulman<sup>1</sup>; J. Zinck<sup>1</sup>; S. L. Skeith<sup>1</sup>; S. Thomas<sup>1</sup>; D. H. Chow<sup>1</sup>; E. T. Croke<sup>1</sup>; H. L. Dunlap<sup>1</sup>; K. S. Holabird<sup>1</sup>; M. A. Morgan<sup>2</sup>; S. Weinreb<sup>2</sup>; <sup>1</sup>HRL Laboratories, LLC, RL92, 3011 Malibu Canyon Rd., Malibu, CA 90265 USA; <sup>2</sup>Caltech, EE, 1201 E. California, Pasadena, CA 91125 USA

We have developed a new type of quantum tunneling diode based on the Type II InAs/GaSb heterostructure system. Unlike resonant tunneling diodes, it has already demonstrated clear potential for practical application, in low power millimeter wave RF radiometry, as its performance is superior to that of existing commercially available solutions. The primary application is in millimeter wave imaging, which has the ability to view through a variety of environmental conditions such as fog, precipitation, smoke, and dust, as well as building walls and clothing. The diode is based on a single barrier InAs/AlSb/GaAlSb heterostructure. The principal of operation is similar to that of an Esaki backward diode in that the controlling current mechanism is interband tunneling between adjacent energetically offset semiconductor regions. The Type II band gap line-up between InAs and GaSb, where the conduction band minimum of InAs lies energetically below the valence band maximum of GaSb, creates a natural asymmetry in the current flow with bias direction. The resulting curvature in the I(V) characteristic is ideal for zero bias direct detection or mixing with low local oscillator power. The diodes have a high frequency response and are relatively insensitive to process variables. They are also relatively insensitive to temperature, as the dominant current transport process is tunneling, not thermal excitation over a barrier as in p-n junction or Schottky diodes. Here we discuss the status of our understanding of the physical mechanisms controlling the device behavior. Although the basic principles are known, we find that the details of the interfaces and the band offsets critically affect optimization of the device. For example, recent reports have suggested that the character of the interfaces plays an important role in interband resonant tunneling transport. In our parametric growth studies, we have explored the use of atomic layer epitaxy (ALE) to produce controlled abrupt interfaces. Our results to date indicate that interface engineering with ALE has a deleterious effect on the diode curvature when compared to the standard growth method. The details of the interface can influence the curvature through at least two effects: (1) changing the heterojunction band offsets which gate the current flow and (2) introducing local electric fields which distort the potential profile near the interfaces. We will present data and theoretical modeling which accounts for the influence of the interface.

#### 11:40 AM

**D6, InSb Heterostructure Bipolar Transistor Operating at Room Temperature:** T. J. Phillips<sup>1</sup>; T. Ashley<sup>1</sup>; T. M. Burke<sup>1</sup>; A. B. Dean<sup>1</sup>; <sup>1</sup>QinetiQ, Inc., St. Andrews Rd., Malvern WR14 3PS UK

We have previously demonstrated room temperature operation of InSb FETs using the technique of carrier exclusion/extraction. In this paper we show that ambient temperature operation of bipolar devices can also be achieved. The performance of transistors (both FET and bipolar) made from narrow bandgap semiconductors is limited by the effect of intrinsic carriers, which cause excess leakage in the off-state, and also contribute to impact ionisation. We have pioneered the use of carrier exclusion/extraction to reduce the carrier concentration in the

active region of a device by many orders of magnitude. This technique has now been applied to bipolar devices. The device design is similar to a conventional bipolar design, with InSb used for all layers except for the emitter, which is made from  $\text{Al}_{0.05}\text{In}_{0.95}\text{Sb}$  and provides a valence band barrier at the emitter-base junction. The base is highly p-type doped, but at present does not contain the p++ implant that will provide the full carrier extraction benefit. However the base can still be reverse-biased to extract carriers from (mainly) the low-doped collector region. The emitter size is  $6\ \mu\text{m} \times 25\ \mu\text{m}$ , and the collector size  $22\ \mu\text{m} \times 25\ \mu\text{m}$ . The resulting device shows low voltage output characteristics, with drain voltages up to 0.6 V and base voltages up to 0.25 V (0.05 V steps). The two lowest lines on the output characteristic are with a negative bias applied to the base, showing how the carrier extraction technique reduces leakage and suppresses breakdown (in fact at negative base voltages the device shows a breakdown voltage of over 1.2 V). The device also shows excellent transconductance, as shown in the characteristic above, limited at higher current by series resistance in the device, which needs optimising. The base-emitter diode shows a reverse current, even at positive base voltages, due to the removal of the thermally generated carriers from the device, and passes through zero current at  $V_{be} = 0.25\ \text{V}$ . Because of this, the differential current gain is very large (hence the output characteristic above is shown with base voltage as the parameter). AC measurements on these  $6\ \mu\text{m}$  emitter devices are very promising, showing an fT of over 25 GHz in a device not optimised for high speed performance. Modelling shows that addition of a p++ implanted base contact results in a factor of eight reduction in leakage current. It also shifts the base-emitter turn-on voltage down towards zero. Scaling of the device leads to a predicted fT of over 600 GHz for devices with  $1\ \mu\text{m}$  emitters.

## Session E: Materials Integration: Wafer Bonding and Alternative Substrates - I

Wednesday AM      Room: UCEN Flying A  
June 26, 2002      Location: University of California

*Session Chairs:* Peter Moran, Michigan Technological University, 1400 Townsend Dr., Houghton, MI 19931 USA;  
Matt Seaford, RF Microdevices, 7628 Thorndike Ln., Greensboro, NC 27409 USA

### 10:00 AM

**E1, Testing the Feasibility of Strain Relaxed Compliant Substrates:** *M. Kostrzewa*<sup>1</sup>; G. Grenet<sup>1</sup>; P. Regreny<sup>1</sup>; J. L. Leclercq<sup>1</sup>; F. Bessueille<sup>1</sup>; N. Mokni<sup>2</sup>; A. Danescu<sup>2</sup>; F. Sidoroff<sup>2</sup>; G. Hollinger<sup>1</sup>; <sup>1</sup>Ecole Centrale de Lyon, LEOM, UMR CNRS 5512, Ecully 69134 France; <sup>2</sup>Ecole Centrale de Lyon, LTDS, UMR CNRS 5513, Ecully 69134 France

To prepare compliant substrates, the most evident approach is to insert a viscous layer in between the thin seed film and the host substrate. Several technological problems have to be solved before actually evidencing the compliant phenomenon itself. First, a sticking material has to be found. It has to be viscous at growth temperatures, compatible with epitaxial processes and appropriate to successfully bond a thin semiconductor layer on a host substrate. Second, the surface quality of the thin seed layer after all the technological steps has to be good enough to allow high quality epitaxial regrowth. Low viscosity borophosphosilicate glass films has been used by several groups. They found that the strain relaxation is accompanied by a buckling which can be eliminated only by patterning the strained films into small areas. In order to learn more about this particular relaxation mechanism (and especially how it could affect the seed film lateral dimensions), we have studied the way an ultrathin epitaxial  $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$  layer elastically relax when stuck on InP or Si substrate using a thick wax layer (with a very low viscosity at room temperature). By freeing the study from difficulties inherent to a real epitaxial overgrowth (high-vacuum, high-temperature) this approach has allowed us direct and time-monitored morphological observations at room-temperature. Moreover, we have performed what can be seen as

the reverse process of an epitaxial growth, i.e., the chemical etching of the initial InP substrate. The experimental results clearly show how a mesa relax both by gliding its edges and by buckling its central area. The competition between these two relaxation processes is discussed via recently published theoretical backgrounds. Finally, we will discuss what can be issued from this theoretical-to-experiment confrontation in terms of compliance understanding and feasibility.

### 10:20 AM Student

**E2, High Ge-Content Relaxed  $\text{Si}_{1-x}\text{Ge}_x$  Layers by Relaxation on Compliant Substrate with Controlled Oxidation:** *Haizhou Yin*<sup>1</sup>; Karl D. Hobart<sup>2</sup>; Rui Huang<sup>3</sup>; Jim Liang<sup>3</sup>; Zhigang Suo<sup>3</sup>; Sean R. Shieh<sup>4</sup>; Thomas S. Duffy<sup>4</sup>; James C. Sturm<sup>5</sup>; <sup>1</sup>Princeton University, Electl. Eng., Princeton, NJ 08544 USA; <sup>2</sup>Naval Research Laboratory, Washington, DC 20357 USA; <sup>3</sup>Princeton University, Princeton Matls. Inst. & Dept. of Mechl. & Aeros. Eng., Princeton, NJ 08544 USA; <sup>4</sup>Princeton University, Dept. of Geosci., Princeton, NJ 08544 USA; <sup>5</sup>Princeton University, Ctr. for Photonics & Optoelect. Matls. & Dept. of Electl. Eng., Princeton, NJ 08544 USA

There has been increasing interest in compliant substrates for integration of heterogeneous epitaxial materials. In this talk, borophosphosilicate glass (BPSG) on silicon is used as a compliant substrate to allow the relaxation of strained SiGe islands, a process which can allow relaxed layers to be obtained without the formation of misfit dislocation observed in graded SiGe buffers. Previous work has shown that relaxed SiGe on Si by this method is limited to small islands (less than 30micron) and low Ge fraction (less than 30%), with the buckling of the compressive SiGe layers as a fundamental limit. In this paper, we describe two key improvements to allow 200micron islands with up to 65% Ge to be relaxed: (i) oxidation of the SiGe layers to increase the Ge fraction, and (ii) the use of a deposited oxide to prevent buckling and control the oxidation rate. A wafer of 30nm-strained- $\text{Si}_{0.7}\text{Ge}_{0.3}/25\text{nm-Si}/200\text{nm-BPSG/Si}$  was fabricated by bonding and "Smart-cut" as in ref. 1. SiGe islands of sizes 10-500micron were then patterned. Long anneals at 875°C were carried out to achieve intermixing of Ge and relaxation of the islands, which yielded relaxed 55nm-thick  $\text{Si}_{0.84}\text{Ge}_{0.16}$  islands. Raman spectroscopy was used to independently determine both the Ge content and strain status of SiGe islands. This sample was oxidized from 800°C to 900°C to raise Ge content due to preferential thermal oxidation of Si atoms in the alloys. Two problems emerged during the oxidation process: (1) Surfaces of islands buckled due to the strain increase from higher Ge content and the island thinning; (2) the uniformity of Ge content across islands was poor, because the surface Ge content of islands is believed to determine the interface oxidation reaction and it is difficult to control the surface condition as Ge snowplows into the alloy during oxidation. A layer of PECVD oxide on the top was used to solve these problems. It effectively increases the island thickness, making them stiffer and consequently less prone to buckling. Furthermore, effect of the SiGe surface on oxidation is removed, because the oxidation process is now largely limited by the diffusion of oxidant through the top oxide. The oxidation rate can be well controlled by the thickness of the oxide layer. Without this capping layer, a lateral lattice constant larger than that of a relaxed  $\text{Si}_{0.7}\text{Ge}_{0.3}$  on 200 $\mu\text{m}$  islands could not be achieved due to buckling and oxidation rate variations. However, with the capping process, uniform 200 $\mu\text{m}$  islands with fully relaxed  $\text{Si}_{0.4}\text{Ge}_{0.6}$  were achieved. In smaller fully relaxed islands Ge content over 70% has been achieved. This is far higher than the effective Ge substrate content (i.e. the in-plane lattice constant of a relaxed layer) of  $\text{Si}_{0.73}\text{Ge}_{0.27}$  previously reported using the oxidation technique. This work is supported by DARPA and ARO.

### 10:40 AM

**E3, Strain Relaxation in Wafer-Bonded SiGe/Si Heterostructures Due to Viscous Flow of an Underlying Borosilicate Glass:** *Peter Morán*<sup>1</sup>; K. D. Hobart<sup>2</sup>; <sup>1</sup>Michigan Technological University, Matls. Sci. Dept., 409 MME Bldg., Houghton, MI 49931 USA; <sup>2</sup>Naval Research Laboratory, 4555 Overlook SW, Washington, DC 20375 USA

We report a high-resolution x-ray diffraction (HRXRD) study of relaxation in a strained semiconductor heterostructure removed from its native substrate, bonded to a glass substrate, and subsequently heated. The data is consistent with the type of relaxation that would result from viscous flow of the underlying glass. It is not consistent with the type of relaxation that would result from an enhancement in misfit dislocation nucleation and/or threading dislocation glide due to a sub-surface bonded

interface with in invicid glass. A 100nm Si<sub>0.81</sub>Ge<sub>0.19</sub> film was grown on a conventional 4" Si substrate and on an SOI substrate consisting of 100nm of Silicon with a 400nm buried SiO<sub>2</sub> layer. The heterostructure grown on the SOI substrate was then bonded to a Corning 7740 glass wafer and the bulk of the original SOI wafer was removed so that just the 100nmSiGe/100nmSi heterostructure (capped by 400nm of SiO<sub>2</sub>) bonded to the glass wafer remained. HRXRD showed the SiGe layer to be fully strained on both the conventional Si substrate and in the bonded heterostructure. 3cm by 3cm die of the heterostructure on the Si substrate and the heterostructure bonded to the glass substrate were then heated for 1 hour to a temperature (700°C) at which the viscosity of the glass substrate was reduced to 109 Poise. Subsequent HRXRD of the structures showed the SiGe layer on the Si substrate to have remained fully strained. HRXRD measurement of the absolute lattice parameters of the SiGe film and the Si template in the bonded heterostructure showed that, upon heating, the strain partitioned between the SiGe film and the Si template according to their relative thickness in roughly the proportion that would be expected if the bonded heterostructure were a free-standing film. The 004 diffraction data shown below, along with additional data on this materials system, will be discussed in terms of what can be inferred about the mechanism of substrate compliance due to viscous flow of an underlying glass.

#### 11:00 AM

**E4, Ultra High Precision of the Tilt/Twist Misorientation Angles in Silicon/Silicon Direct Wafer Bonding:** *F. Fournel*<sup>1</sup>; H. Moriceau<sup>1</sup>; B. Aspar<sup>1</sup>; N. Magnea<sup>2</sup>; J. Eymery<sup>2</sup>; K. Rousseau<sup>2</sup>; J. L. Rouviere<sup>2</sup>; <sup>1</sup>CEA, LETI/Dept. of Silicium Tech., 17 rue des Martyrs, Grenoble 9 France 38054; <sup>2</sup>CEA, Dept. of Fundamental Rsrch. sur la Matiere Condensee, 17 rue des Martyrs, Grenoble 9 France 38054

New substrates for epitaxy with a nanometric sub-surface patterning are elaborated by direct bonding of ultra thin films of silicon onto Si wafers. Due to the misorientation of the two crystals, the direct bonding produces nanometric networks of dislocations localized at the bonding interface. An original direct wafer bonding process has been developed to accurately control both the bonding interface twist and tilt angles between the two bonded monocrystalline crystals. This process is based on the bonding of twin surfaces coming from a single wafer, using for instance the Smart Cut &#61730; process. The twist angle is achieved with an accuracy of about  $\pm 0.005^\circ$  without any alignment measurement based on diffraction techniques, but only by positioning lithographic marks. Using such process, pure twist-bonded interfaces have been made between two (001) bonded silicon surfaces. Pure square dislocation network is so obtained at the bonding interface. HREM observations show the excellent regularity of such a network without the well known mixed dislocations which usually appear due to the tilt disorientation between the two crystal. Grazing incidence X-Ray diffraction confirms the very good precision of the bonding alignment and the regularity of the network over several mm<sup>2</sup>.

#### 11:20 AM

**E5, Observation and Simulation of Anisotropic Diffusion of Hydrogen at Hydrophobic Wafer Bonded Interface:** *Robert Esser*<sup>1</sup>; Karl D. Hobart<sup>1</sup>; Ron W. Rendell<sup>1</sup>; Francis J. Kub<sup>1</sup>; <sup>1</sup>Naval Research Laboratory, 6813, 4555 Overlook Ave. SW, Washington, DC 20375 USA

The formation of voids at hydrophobic bonded wafer interfaces has been studied for some time. It is generally thought that the source of the voids is a combination of hydrocarbons adhered to the surface combined with the hydrogen released from surface dihydride. The gasses are evolved at 300-400°C and form voids at the bond interface after the wafers are annealed. The annealing step is required to form a mechanically strong bond. It is possible to remove the voids by an 1100°C anneal, but this precludes the integration of processed wafers. The presence of voids has a deleterious effect on the performance of any electronic devices that are formed on the bonded structure, in particular, when the bond interface is an active region. Initial experiments were aimed at reducing the number of voids by introducing trenches or vents for the escaping gas, these included wafers with laser drilled holes and grids of etched trenches. While the drilled wafers showed no appreciable effect on the presence of voids, the trench grids showed a dramatic reduction. Further experiments were performed to ascertain the discrepancy between these results. A possible explanation is anisotropic diffusion of gasses at the bond interface. To verify this hypothesis, experiments were performed utilizing an array of etched trenches. It was found that the interfacial gasses

diffuse preferentially along the <110> directions of the (001) silicon surface at the bond interface. This is shown by a study of the occurrence and pattern of voids in low temperature hydrophobic wafer bonding experiments. An array of trenches is etched into the surface of one of the wafers, and the wafers are bonded so that the major flats are aligned within approximately one degree. During anneal, gasses are generated at the bond interface, and after some diffusion, nucleate to form voids. The diffusion of gasses is indirectly observed by the presence or absence of voids. The reduction of voids along the <110> directions near the etched trenches but not along other crystallographic directions indicates anisotropic diffusion. Along the <110> directions near the etched trenches, the number of voids is dramatically reduced, while in other directions, the number of voids is only slightly reduced. The diffusion behavior was numerically simulated with a stochastic dynamics model. Constraints were added to the model to limit atomic movement to the x and y, <011> directions. Boundary conditions were absorbing at the etched trenches and at randomly located void nucleation sites. Periodic boundaries were included to simulate an array of etched trenches. The radius of the nucleation sites as well as the length and periodicity of the etched trenches were adjustable. Histograms of void formation and location were made and show good agreement with the experimental results verifying anisotropic diffusion.

#### 11:40 AM

**E6, The Effects of Plasma Exposure Used for Bonding on the Electrical Characteristics of the Treated Wafers:** *Cindy Colinge*<sup>1</sup>; Stefan Bengtsson<sup>2</sup>; Petra Amirfeiz<sup>2</sup>; Anke Sanz-Velasco<sup>2</sup>; <sup>1</sup>California State University-Sacramento, Dept. of Electl. Eng., 6000 J St., Sacramento, CA 95819-6019 USA; <sup>2</sup>Chalmers University of Technology, Dept. of Microelect. Ed, S-412 96 Göteborg, Sweden

Wafer bonding using an ICP oxygen plasma exposure can greatly increase bond strength without any anneal process (i.e., room temperature anneal). In this talk we will present CV data for two types of plasma exposed wafers and compare the results to monitor and "ideal" CV data. In the first case, wafers were first etched in HF to remove any native oxide prior to plasma exposure. The wafers were then measured immediately using a mercury probe system. The wafers were re-measured one day and four days later while sitting at room temperature in a clean environment. In the second experiment, wafers with a known thermal oxide thickness were plasma exposed. These wafers were measured as a function of time, as described in the first experiment, and after temperature exposure. As part of the experiment, wafers with plasma treatment were subjected to varying temperatures from 50°C to 100°C and re-measured. The trend in the threshold voltage shift was noted and tended toward the monitor wafer value as temperature exposure was increased. CV data suggests that plasma exposure greatly affects the wafer either by radiation effects or ion effects and therefore this affects CV curves due to the charges and/or trap levels in the oxide. When comparing the results to a non-treated (no plasma treatment) thermal oxide wafer, there is a dramatic shift in threshold voltage and an increased curvature of the CV plots verifying charges or traps present. The CV measurements were taken using a mercury probe, and therefore the wafers in all cases were not exposed to high temperatures, simply room temperature, except for the one experiment where temperature was varied from 50-100°C. For the wafers which were exposed without any previous native oxide (HF dipped prior to plasma treatment) leakage current was observed. The current followed a Fowler-Nordheim mechanism with the wafer biased in the accumulation region. In the depletion region, the leakage current was minimal. These two measurements may be a result of the porous nature of the oxide formed during plasma treatment. It should be noted however, that the CV plots of these wafers also showed a shift in threshold voltage as well as a curvature or spreading out of the plots. The results of these two types of exposed wafers, one with an initial oxide and one without any initial oxide, will be discussed in this talk. In addition, the ramifications of plasma bonding for the fabrication of devices will be discussed.

## Session F: Silicon Carbide: Processing

Wednesday AM Room: UCEN Lobero  
June 26, 2002 Location: University of California

*Session Chair:* Phil Neudeck, NASA Glenn Research Center,  
21000 Brookpark Rd., MS 77-1, Cleveland, OH 44135 USA

### 10:00 AM

**F1, Temperature Dependence of Channel Mobility in Nitric Oxide Annealed MOSFETs on (0001) 4H-SiC:** *Chao Y. Lu*<sup>1</sup>; James A. Cooper<sup>1</sup>; Takashi Tsuji<sup>2</sup>; G. Y. Chung<sup>3</sup>; John R. Williams<sup>3</sup>; K. McDonald<sup>4</sup>; Leonard C. Feldman<sup>4</sup>; <sup>1</sup>Purdue University, Sch. of Electl. & Compu. Eng., Electl. Eng. Bldg., W. Lafayette, IN 47907 USA; <sup>2</sup>Fuji Electric Company, Corporate Tech. Planning Office, Tokyo, Japan 141-0032; <sup>3</sup>Auburn University, Physics Dept., Auburn, AL 36849 USA; <sup>4</sup>Vanderbilt University, Physics Dept., Nashville, TN 37235 USA

Post-oxidation-annealing (POA) in nitric oxide (NO) has been shown to reduce the density of interface states ( $D_{it}$ ) in the upper half of the bandgap on 4H-SiC and to increase the inversion channel mobility in 4H-SiC MOSFETs. However, little information is available on the temperature dependence of mobility on NO annealed MOSFETs. In this paper we report measurements of the temperature dependence of inversion layer electron mobility in NO-annealed 4H-SiC MOSFETs. The MOSFETs in this study are formed on p-type epilayers doped  $2.5 \times 10^{16} \text{ cm}^{-3}$  on heavily-doped p+ 4H-SiC substrates. Nitrogen source/drain implants are activated at 1400°C for 40 min in Ar. The gate oxide is grown in wet  $\text{O}_2$  at 1150°C for 2.5 hours with an in-situ Ar anneal for 1 hour, followed by a 2 hour re-oxidation anneal in wet  $\text{O}_2$  at 950°C. A post-oxidation NO anneal is performed at 1175°C. The polysilicon gate is deposited by LPCVD at 625°C for 1 hour and doped with phosphorus from a spin-on source at 900°C for 1 hour. Ohmic contacts for the source/drain and base are Ni and Al respectively, and the contact anneal is performed at 850°C for 5-6 min. in vacuum. MOSFETs without an NO post-oxidation anneal exhibit broadened gate turn-on characteristics due to high  $D_{it}$ . In contrast, in identical samples receiving an NO post-oxidation anneal, the  $I_D/(g_m)^{0.5}$  vs.  $V_G$  curves are linear, and the threshold voltage can be sharply defined by the intercept. In addition, the effective mobility of NO-annealed samples has the form  $\mu_0/(1+\epsilon(V_G-V_T))$  assumed by Ghibaudo's technique, allowing this method to be used to extract parameters for effective mobility. Eighteen long-channel MOSFETs with average oxide thickness of 54nm (determined by C-V) are measured between room temperature and 350°C. For each device measured, the mobility given by  $\mu_0/(1+\epsilon(V_G-V_T))$  agrees well with the effective mobility calculated by  $g_D$  divided by channel electron density. By fitting the mobility parameters for all NO-annealed devices in the least squares sense, we obtain the following fitting coefficients for the third-order polynomial for each parameter:  $\mu_0 = 48.5 + 0.191 T - 1.15 \times 10^{-3} T^2 + 1.58 \times 10^{-6} T^3$ ;  $V_T = 0.882 - 1.48 \times 10^{-2} T + 4.62 \times 10^{-5} T^2 - 5.02 \times 10^{-8} T^3$ ;  $\epsilon = 2.33 \times 10^{-2} - 1.92 \times 10^{-5} T + 1.11 \times 10^{-7} T^2 - 2.75 \times 10^{-10} T^3$ , where T is temperature in Celsius and  $20 \leq T \leq 350$ . The mobility decreases monotonically as temperature increases, indicating that phonon scattering is the main scattering mechanism in samples receiving the NO anneal. In contrast, Coulomb scattering is dominant in samples that did not receive the NO anneal. This work is supported by ONR grant N00014-01-1-0072 (Purdue) and by DARPA/EPRI grant MDA972-98-1-0007/W08069-05 (Auburn and Vanderbilt).

### 10:20 AM Student

**F2, The Effect of Crystal Orientation and Post-Oxidation NO Anneal on Inversion Layer Electron Mobility in 4H-SiC UMOSFETs:** *Imran A. Khan*<sup>1</sup>; James A. Cooper<sup>1</sup>; T. Isaacs-Smith<sup>2</sup>; J. R. Williams<sup>2</sup>; L. C. Feldman<sup>3</sup>; <sup>1</sup>Purdue University, ECE, Box #253, W. Lafayette, IN 47907 USA; <sup>2</sup>Auburn University, Physics, Auburn, AL 36849 USA; <sup>3</sup>Vanderbilt University, Dept. of Physics & Astron., Nashville, TN 37235 USA

Recent reports have demonstrated a significant increase in inversion layer electron mobility on the (0001) plane of 4H-SiC following a post-oxidation anneal (POA) in nitric oxide (NO). Other groups have re-

ported high electron mobilities on the (112b0) plane of 4H-SiC without an NO POA, as measured on epitaxial wafers oriented in the [112b0] direction. These results are particularly interesting for power UMOSFETs on the (0001) silicon-face of 4H-SiC, since in these devices the inversion channel is formed on a-axis crystal planes such as the (112b0) and (11b00) planes that are exposed by reactive ion etching (RIE). Unfortunately, there have been no reports to date on the inversion layer mobility of surfaces exposed by RIE. There have also been no reports on the effects of a post-oxidation NO anneal on inversion layer mobility in the (112b0) plane. In this paper we report the first measurements of inversion layer electron mobility on the (112b0) and (11b00) planes in a UMOSFET structure. We also report the effects of RIE etch conditions and post-oxidation NO annealing on the inversion layer mobility. Test structures are fabricated on the (0001) surface of epitaxial 4H-SiC wafers. Two epilayers are grown on an 8° off-axis n+ SiC substrate. The first epilayer is 1.5µm thick, doped p-type  $1.6 \times 10^{17} \text{ cm}^{-3}$  with aluminum. The second epilayer is 0.5µm thick, doped n-type  $2 \times 10^{19} \text{ cm}^{-3}$  with nitrogen. Gate trenches are formed by RIE in a mixture of  $\text{SF}_6$  and  $\text{O}_2$ . Multiple crystal orientations are investigated by patterning gate trenches oriented at 15° intervals between and including the (112b0) and (11b00) planes. The gate oxide is formed by depositing a thin layer of polysilicon by LPCVD and oxidizing at 950°C in wet  $\text{O}_2$ . The oxidation is terminated by a 950°C 30 min. in-situ Ar anneal. Some samples are then given a post-oxidation anneal in NO using procedures described elsewhere. Inversion layer electron mobilities are measured on different crystal planes and for different RIE etch conditions. While the different crystal orientations and RIE etch conditions do not have a significant effect on mobility, a post-oxidation anneal in NO effectively doubles the inversion layer mobility. For samples without an NO anneal, the field-effect mobility peaks at 21  $\text{cm}^2/\text{Vs}$  and decreases to about 10  $\text{cm}^2/\text{Vs}$  at an oxide field of 3 MV/cm. For identical samples with an NO post-oxidation anneal, the field-effect mobility peaks at 43  $\text{cm}^2/\text{Vs}$  and decreases to about 25  $\text{cm}^2/\text{Vs}$  at an oxide field of 2.75 MV/cm. This is a significant increase in inversion layer mobility in a realistic UMOSFET structure, and points the way to achieving higher performance in 4H-SiC power UMOSFETs. This work is supported by ONR grant N00014-01-1-0072 (Purdue) and by DARPA/EPRI grant MDA972-98-1-0007/W08069-05 (Auburn and Vanderbilt).

### 10:40 AM

**F3, Bonding Changes Across the Silicon Dioxide-Silicon Carbide Interface: Effect of Oxidation Temperature and Reoxidation Conditions:** *Kai-Chieh Chang*<sup>1</sup>; N. T. Nuhfer<sup>1</sup>; Lisa M. Porter<sup>1</sup>; <sup>1</sup>Carnegie Mellon University, MSE Dept., REH 149, Pittsburgh, PA 15213 USA

Thermally grown  $\text{SiO}_2/6\text{H-SiC}$  (0001) and (000-1) interfaces were investigated using a high-resolution transmission electron microscope (HRTEM) equipped with electron energy-loss spectroscopy (EELS). The HRTEM images showed that the 6H stacking sequence remained intact following wet oxidation at temperatures between 950 and 1250°C. However, EELS analyses revealed a layer within a 'transition layer'  $\text{Si}_x\text{C}$  ( $x > 1$ ) that contains a change in the local bonding arrangements around the Si and C atoms. For example, while the C ionization edge within the SiC bulk material was characteristic of sp<sup>3</sup> bonding only, the C edge close to the interface was characteristic of a mixture of sp<sup>2</sup> and sp<sup>3</sup> bonding. The thickness of this layer is a function of the oxidation temperature and the crystal orientation. A lower oxidation temperature (950°C) reduced the thickness of the transition layer. Reoxidation at 950°C for 3 hrs had a similar effect. The change in the bonding type is attributed to unsaturated dangling bonds. In addition, high-resolution imaging indicates the presence of a thin, chemically distinct layer (e.g., a silicon oxycarbide) located precisely at the interface, which may contribute to the observed bonding changes. This layer was not removed after reoxidation. In this presentation we will summarize the chemical and microstructural changes at the  $\text{SiO}_2/6\text{H-SiC}$  interface as a function of oxidation temperature, substrate orientation and reoxidation conditions and will discuss the implications for reducing the high interface state densities ( $D_{it}$ ).

### 11:00 AM

**F4, Low-Dose Nitrogen N-Type Implants in 4H-SiC:** *Nelson Saks*<sup>1</sup>; S.-H. Ryu<sup>2</sup>; Anant Agarwal<sup>2</sup>; <sup>1</sup>Naval Research Laboratory, Code 6813, 4555 Overlook Ave., Washington, DC 22309 USA; <sup>2</sup>CREE, Inc., 4600 Silicon Dr., Durham, NC 27703 USA

Low-dose nitrogen implants are needed to fabricate lightly-doped n-type regions in SiC power devices. Typical applications include threshold shift implants in MOSFETs and drift layers in high voltage lateral



RESURF transistors. To date, most research on n-type implantation has concentrated on reducing the sheet resistance of heavily-doped regions using high implant doses  $>10^{15}/\text{cm}^2$ . Here we report on low-dose nitrogen implants in 4H-SiC. P-type epitaxial SiC layers were implanted at 600°C using multiple energy implants to obtain box profiles. Sample #1 was implanted with  $7.66 \times 10^{12} \text{ N/cm}^2$  and annealed uncapped at 1300°C in argon. Sample #2 was implanted with  $1.85 \times 10^{12} \text{ N/cm}^2$  and annealed uncapped at 1600°C in a silicon-overpressure to prevent excess surface roughness. Hall measurements of electron mobility and free electron density were made from 77K to 500K using a Hall scattering factor of 1.0. Measured electron Hall mobilities at 300K are 438 and 735  $\text{cm}^2/\text{Vs}$  for samples #1 and #2, respectively. These values are equal to the bulk mobilities in 4H-SiC epitaxial layers when corrected for the doping density<sup>1</sup>. Measured activation rates of the implanted nitrogen, obtained using a best fit of the temperature-dependent free electron density to a charge neutrality model<sup>2</sup>, are 55% and 71% for samples #1 and #2, respectively. These activation rates in 4H-SiC are somewhat lower than previously reported for low-dose nitrogen implants in 6H-SiC of ~100%<sup>3</sup>. Energy levels Edh and Edk (for the h and k levels for the nitrogen donor) measured in samples #1 and #2 are in good agreement with energies measured in epitaxially grown layers (0.06 and 0.10 eV, respectively<sup>4</sup>). The relative densities of the h and k levels are nearly 1:1 as expected for 4H-SiC. The measured compensation concentrations, which arise from un-annealed implant damage, are 30% and 17% of Nd for samples #1 and #2, respectively. These compensation levels are considerably higher than reported for nitrogen implants in 6H-SiC of 1.5% after annealing at 1400°C<sup>3</sup>. In summary, good quality lightly doped n-type layers with bulk electron mobility have been fabricated by nitrogen implantation. A higher activation rate of the implanted nitrogen and a lower compensation level were obtained in sample #2 annealed at a higher temperature. However, the compensation level is still much higher than observed in 6H-SiC, indicating that even higher anneal temperatures may be desirable. <sup>1</sup>W. J. Schaffer, G. H. Negley, K. G. Irvine, and J. W. Palmour, *Mat. Res. Soc. Symp.* 339, 595 (1994); <sup>2</sup>M. Schadt, G. Pensl, R. P. Devaty, W. J. Choyke, R. Stein, and D. Stephani, *Appl. Phys. Letts.* 65, 3120, Dec. (1994); <sup>3</sup>N. S. Saks, A. K. Agarwal, S. S. Mani, and V. S. Hegde, *Appl. Phys. Letts.* 76, 1896, Apr. (2000); <sup>4</sup>W. J. Choyke and G. Pensl, *MRS Bulletin*, p. 25, Mar. (1997).

#### 11:20 AM Student

**F5, Laser-Direct Write and Doping of Wide Bandgap Materials:** *Islam Salama*<sup>1</sup>; N. R. Quick<sup>2</sup>; Aravinda Kar<sup>1</sup>; <sup>1</sup>School of Optics/CREOL, *Matls. Eng.*, Orlando, FL 32816 USA; <sup>2</sup>Applicote Associate, 894 Silverado Ct., Orlando, FL 32746 USA

Laser-direct write technique is utilized to introduce stable conversion in electric properties of wide bandgap materials such as diamond and silicon carbide. N-type doped, p-type doped and highly conductive tracks are created on different SiC polytypes. Metal-like conductive tracks are created by laser irradiation in inert atmosphere while the doped tracks are generated by laser irradiation in nitrogen and in TMA and argon mixture for the n-type and the p-type doping, respectively. The tracks irradiated in inert gas exhibit higher electric resistance (1-2 kOhm) than those irradiated in dopant containing environment (0.1-02 kOhm). While laser-irradiation in oxygen containing environment created a thin oxide layer at the SiC surface with an attendant increase in electric resistance (from 300 to 320 kOhm), laser irradiation in air produces conductive tracks with electric resistance comparable to those obtained in laser-argon treatment (2kOhm). The extent of the conversion in electric resistance increases with laser power density having a critical value below which the variation in electric resistance is minimum. The critical power density ( $P_c$ ) depends sensitively on the irradiation environment and surface characteristics. At a given power density (higher than  $P_c$ ) the conversion increases asymptotically with the number of irradiation passes. The asymptotic value of the electric resistance for the laser-nitrogen-treated sample is lower than that for the laser argon-treated one suggesting the doping effect of nitrogen. Different analytical (XPS, XRD, AFM, SEM, TEM and Raman spectroscopy) studies of the laser-treated tracks reveal the presence of carbon-rich phases having a finer microstructure than the as-received sample. The XPS core level analysis suggests the incorporation of nitrogen atoms in the SiC lattice by bonding to Si rather than to carbon atoms. The conversion in electric resistance after laser treatment in inert gas (argon) is mainly due to laser-thermal effect, i.e., laser heating causing peritectic reaction in SiC. In the case of irradiation

in nitrogen and in a mixture of TMA and argon, the conversion is attributed partly to the thermal effect and partly to the incorporation of nitrogen and aluminum as dopants into the SiC matrix. Laser-fabrication of n-type schottky barrier junction on a diamond like carbon (DLC) substrate is demonstrated. Both capacitance-voltage and current-voltage characteristics of the laser-fabricated junction are measured and used to determine the dopant profile along the junction width. Laser direct-write technique provides a reduced-number of steps, highly controllable, and cost-effective tool for rapid prototyping as well as commercial fabrication of wide bandgap semiconductor devices. This technique is capable of metallization, dielectric synthesis and selective area doping as well as etching of a wide variety of semiconductor materials. It can also be utilized as a secondary process for defect annealing, doping activation and conductivity control of ion-implanted and as-grown substrates.

11:40 AM

F6, Late News

## Session G: Nitrides: Light Emitters and Piezoelectric Effects

Wednesday PM

Room: Lotte Lehmann

June 26, 2002

Location: University of California

*Session Chairs:* Christian Wetzel, Uniroyal Optoelectronics, 3401 Cragmont Dr., Tampa, FL 33619 USA; Russell D. Dupuis, University of Texas, 10100 Burnett Rd., Austin, TX 78758 USA

#### 1:20 PM Student

**G1, AlGa<sub>x</sub>N/GaN and AlGa<sub>x</sub>AlGa<sub>1-x</sub>N UV Light-Emitting Diodes Grown by Metalorganic Chemical Vapor Deposition:** *Ting G. Zhu*<sup>1</sup>; Johnathan C. Denyszyn<sup>1</sup>; Uttiya Chowdhury<sup>1</sup>; Delphine S. Sicault<sup>1</sup>; Michael M. Wong<sup>1</sup>; Jin-Ho Choi<sup>1</sup>; Russell D. Dupuis<sup>1</sup>; <sup>1</sup>University of Texas at Austin, *Electr. & Compu. Eng.*, 10100 Burnet Rd., Bldg. 160, Austin, TX 78712-1100 USA

Wide-bandgap nitride semiconductor materials have attracted more attention for ultraviolet (UV) optoelectronic devices applications recently. A compact, high-efficiency UV light source could be used in chemical identification, medical processes, lighting and displays, and optical data storage. In this study, the Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN and Al<sub>x</sub>Ga<sub>1-x</sub>N/Al<sub>x</sub>Ga<sub>1-x</sub>N LED structures are grown by low-pressure metalorganic chemical vapor deposition in an EMCORE TurboDisc D125 UTM high-speed rotating-disk reactor on 2.0 in. diameter 6H-SiC substrates. The 1mm GaN:Si template layer grown at ~200Torr is employed in the AlGa<sub>x</sub>N/GaN LED structure. The active region consists of 20nm AlGa<sub>x</sub>N:Si (x=0.10) barriers and a 10nm GaN:Si QW for the SQW structure; or three 10nm GaN:Si QWs with 5nm AlGa<sub>x</sub>N:Si (x=0.10) barriers, for the MQW structure. The p-side cladding structures including twenty five-pair [2.5nm AlGa<sub>x</sub>N:Mg (x=0.25)/2.5nm AlGa<sub>x</sub>N:Mg (x=0.10)] superlattice is designed to enhance the hole concentration and the vertical conduction. Good I-V characteristics with differential resistances of 20-30Ω is obtained from both of the single-quantum well (SQW) and multiple-quantum well (MQW) structures. The DC electroluminescence (EL) spectra exhibited single sharp peaks near the GaN bandedge (λ~363nm) and a narrow emission linewidth of 9nm. Light output power measurements were made from the top of the device using a bare-chip geometry configuration. Measurements at I=0.5kA/cm<sup>2</sup> produced a light output intensity of 50iW measured with a calibrated Si p-i-n photodiode, placed about 1cm above the device. By modifying the Al alloy compositions in active region, we have demonstrated the UV LED emitting light at peak wavelength of 341nm. Figure 1 shows the room-temperature EL emission spectra for this UV LED under the various injection currents. The LED structure uses an 1.1μm AlGa<sub>x</sub>N:Si x=0.27 as a template layer. Three 10nm AlGa<sub>x</sub>N:Si (x=0.08) QWs with 5nm AlGa<sub>x</sub>N:Si (x=0.18) barriers form the active region. A twenty five-pair [2.5nm AlGa<sub>x</sub>N:Mg (x=0.30)/2.5nm AlGa<sub>x</sub>N:Mg (x=0.25)] superlattice is implemented as p-type cladding layer. Hall-effect measurements on the same p-type superlattice structure produced in a separate run show a free-hole concentration of p~1.5x10<sup>18</sup> cm<sup>-3</sup> at



300K. To the best of our knowledge, this is the highest free-hole concentration in  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  ( $x > 0.25$ ) thus far reported. The results of a study of p-type SL doping with various barrier and well configurations to improve the device vertical conduction will be presented. The UV LEDs exhibit an operating voltage of 5V at a forward current 20mA. The second peak at 310nm is contributed from the p-type superlattice. It is a clear indication that a shorter-wavelength UV LED is obtainable by varying the Al alloy composition in the active region. Comparative studies of the performance of devices with AlGaIn/GaN or AlGaIn/AlGaIn double-heterostructure, SQW, and MQW active regions will also be discussed.

**1:40 PM**

**G2, Structural, Electrical and Optical Properties of Deep Ultraviolet AlN/AlGaIn Light Emitting Diodes:** *Sergey Nikishin<sup>1</sup>; Gela Kipshidze<sup>1</sup>; Vladimir Kuryatkov<sup>1</sup>; Boris Borisov<sup>1</sup>; Kaigui Zhu<sup>2</sup>; Mark Holtz<sup>2</sup>; Sung N. Chu<sup>3</sup>; Henryk Temkin<sup>1</sup>;* <sup>1</sup>Texas Tech University, Electl. & Compu. Eng., Lubbock, TX 79409-3102 USA; <sup>2</sup>Texas Tech University, Physics, Lubbock, TX 79409 USA; <sup>3</sup>Agere Systems, 600 Mountain Ave., Murray Hill, NJ 07874 USA

Ultraviolet light emitting diodes (LEDs) with emission wavelength as short as 280nm, grown by gas source molecular beam epitaxy with ammonia, are described. The typical multi-quantum well structures (MQW) LED consists of a 40-nm-thick AlN buffer layer deposited on Si(111) or sapphire, followed by a  $\sim 1\mu\text{m}$  thick AlGaIn buffer layer and two superlattice structures, n- and p-type, with the MQW active region placed between them. A 40nm thick layer of AlN is grown to produce a two-dimensional (2D) Al-polar surface. The growth temperatures of AlN buffer layer and Al(Ga)N/AlGaInN superlattices were 830-860°C and 760-800°C, respectively. The average growth rates of AlN and AlGaInN, and AlGaIn and Ga(In)N, were 300 nm/hour and 350 nm/hour, respectively. Two superlattice types, AlGaIn/GaInN and AlN/AlGaInN, doped with Si and Mg were used as n- and p-type cladding layers, respectively. The AlN content in the well is  $\sim 0.1$ . The In content of  $\sim 0.05\%$ , is estimated from the red shift of cathodoluminescence spectra of GaInN and AlGaInN compared to a reference layers of GaN and AlGaIn, respectively. Reflectivity spectra obtained on different AlN/AlGaInN superlattice wafers indicate optical bandgaps ranging from 4.6 to 5.0 eV, consistent with cathodoluminescence spectra. Hall measurements of n- and p-type superlattice structures based on  $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}/\text{GaN}$  show average electron and hole concentrations of  $2 \times 10^{18} \text{ cm}^{-3}$  and  $4 \times 10^{17} \text{ cm}^{-3}$ , respectively. These are doped uniformly with Si (derived from silane) and Mg (derived from an effusion cell). Room temperature hole mobility of  $8 \text{ cm}^2/\text{Vs}$  was measured in p-type superlattices. With AlN/AlGaInN superlattices we obtain hole concentrations of  $(0.7-1.1) \times 10^{18} \text{ cm}^{-3}$ , with the mobility of  $3-4 \text{ cm}^2/\text{Vs}$  and electron concentrations of  $3 \times 10^{19} \text{ cm}^{-3}$ , with the mobility of  $10-20 \text{ cm}^2/\text{Vs}$ , at room temperature. Hall resistivities are very weakly temperature dependent, as expected from in-plane 2D gas structures. These carrier concentrations are sufficient to form effective p-n junctions needed in ultraviolet light emitting diodes. Electroluminescence from our LEDs exhibits complex behavior, strongly influenced by the design of the active region and the device fabrication procedure. Introduction of an undoped well/barrier region between n- and p-type superlattices does not improve carrier confinement but it appears to provide a region of higher radiative recombination and has a large effect on electroluminescence efficiency. In such a structure mesa etching is effective in eliminating lateral conduction. Electroluminescence spectra of the etched structure show predominant emission at 280nm at all currents.

**2:00 PM Student**

**G3, Surface-Emitting Light-Emitting Diode with a GaN Tunnel-Junction Current Aperture:** *Jeon Seong-Ran<sup>1</sup>; Cho Myong Soo<sup>1</sup>; Hung Tran Vinh<sup>1</sup>; Yu Min-A<sup>1</sup>; Yang Gye Mo<sup>1</sup>;* <sup>1</sup>Chonbuk National University, Semiconductor Sci. & Tech. & Semiconductor Physics Rsrch. Ctr., Chonju 561-756 S Korea

We proposed a buried TJ as a current aperture in GaN-based VCSELs and demonstrated a blue surface light emitting diode with a buried TJ current aperture for lateral current confinement. Although the GaN-based vertical-cavity surface-emitting lasers (VCSELs) have attractive wide attention for applications, there have been only a few successful attempts to fabricate optically pumped VCSELs. This is mainly because it is still difficult to grow highly reflective quarter-wave reflectors based on GaN/Al(Ga)N due to large differences in lattice constant and thermal expansion coefficient. In addition, the relatively low conductivity of p-type GaN material makes it difficult to inject a current laterally. In this

work, the buried structures were grown on a c-face sapphire substrate by metalorganic chemical vapor deposition. A  $3.0\mu\text{m}$ -thick Si doped n-type GaN bottom contact layer was formed on a 25nm-thick GaN low-temperature buffer layer, a MQW active layer, consisting of six periods 2 nm/8nm-thick InGaIn/GaN, followed by a 150nm-thick layer of p-type GaN:Mg, a heavily doped  $p^{++}/n^{++}$  tunnel junction, and a 10nm-thick n-type GaN:Si layer. The circular mesas with various diameters (4-32 $\mu\text{m}$ ) were defined by inductively coupled plasma etching to a depth of  $\sim 100\text{nm}$  extending into the Mg doped p-type GaN layer. After formation of various TJ mesas, we carried out regrowth of top contact layer having a 20nm-thick undoped n-type GaN layer and a  $0.33\mu\text{m}$ -thick n-type GaN:Si on the TJ mesas. The surface of the top n-type GaN layer was partially etched until the n-type GaN bottom contact layer was exposed by inductively coupled plasma etching. After then, Ti/Al was deposited on the top n-type GaN surface and the etched bottom n-type GaN surface at the same time. The n-type upper electrode contact with hollow circular window of 50  $\mu\text{m}$ -diameter and n-type lower electrode contact were formed by lift-off. From the near field pattern images of the buried structure surface emitting diodes with various TJ aperture sizes (20 $\mu\text{m}$ , 16 $\mu\text{m}$ , and 8 $\mu\text{m}$ ), we observed that the light emission is just from the inner of window, below where the TJ aperture is. In addition, there is no light emission from the outer of window. This means that the buried TJ mesa has a function of current aperture for lateral current confinement. The bright circular shape of the uniform light emission image indicates a direct evidence of current confinement in the buried TJ mesa. As a result, this work of lateral current injection utilizing a buried TJ aperture represents a significant step toward the realization of a violet/blue current-injected GaN-based VCSEL.

**2:20 PM**

**G4, The Influence of Indium Incorporation on the Optical, Photoluminescence and Lasing Properties of InGaIn, AlInGaIn Films and Quantum Well Structures:** *M. Y. Ryu<sup>1</sup>; E. Kuokstis<sup>1</sup>; C. Q. Chen<sup>1</sup>; J. P. Zhang<sup>1</sup>; J. W. Yang<sup>1</sup>; G. Simin<sup>1</sup>; M. A. Khan<sup>1</sup>; G. G. Sim<sup>2</sup>; P. W. Yu<sup>2</sup>;* <sup>1</sup>University of South Carolina, Dept. of Electl. Eng., 301 S. Main St., Columbia, SC 29208 USA; <sup>2</sup>Kwangju Institute of Science and Technology, Dept. of Info. & Comm., 1 Oryong-dong, Kwangju 500-712 Korea

A complex investigation of the role of indium incorporation into nitride-based ternary and quaternary alloys was carried out using various techniques of laser spectroscopy (photorefectivity (PR), photoluminescence (PL), time-resolved PL, optical gain analysis) in a wide temperature range, as well as methods of structural analysis (atomic force microscopy, X-ray diffraction). InGaIn and AlInGaIn epilayers and their quantum structures were prepared by conventional metalorganic chemical vapor deposition (MOCVD), as well as by pulsed atomic layer epitaxy (PALE) and pulsed MOCVD (PMOCVD) techniques. A comparative study of PL, PL kinetics, stimulated emission and PR properties of InGaIn epilayers within content range of  $0 \leq x \leq 19\%$  revealed blue PL mechanism transformation from optical transitions associated with band states ( $x \leq 5\%$ ) to ones related with density-of-state tails ( $x \geq 5\%$ ). Strict correlation between the positions of low-energy PR oscillation due to the density of states band gap and stimulated emission peak with the change of indium content shows that band-to-band transitions dominate and are responsible for stimulation in highly excited InGaIn samples. Even small (up to  $\sim 3\%$ ) incorporation of In into InGaIn alloy leads to the sufficient increase of recombination decay time showing essential decrease of the role of nonradiative recombination channels in the alloy, whereas further In incorporation leads to the increase of spontaneous PL intensity caused by the localized carriers and/or excitons at band-tails in the In-rich areas. Quaternary alloy AlInGaIn epilayers with small fraction of In (up to 3%) exhibit ultraviolet PL under excimer laser excitation ( $\lambda = 193\text{nm}$ ). However, comparison of different growth techniques showed that PMOCVD method enables one to grow epilayers with the highest PL efficiency. The analysis of temperature and excitation dependent PL spectra, as well as time-resolved PL behavior showed that dominant mechanism of radiative recombination in alloys grown by PMOCVD is associated with band-tail-states transitions whereas for ones grown by PALE technique it is caused by band-to-band transitions. The results obtained in quaternary AlInGaIn-based multiple quantum wells grown by PMOCVD process show them to be very attractive for the active media in ultraviolet light-emitting devices.

**2:40 PM Student**

**G5, GaN Microdisk Fabrication Using Photoelectrochemical Etching:** *Elaine D. Haberer*<sup>1</sup>; Andreas Stonas<sup>2</sup>; Yan Gao<sup>1</sup>; Steven Denbaars<sup>1</sup>; Evelyn L. Hu<sup>2</sup>; <sup>1</sup>University of California–Santa Barbara, Matls. Dept., Santa Barbara, CA 93106 USA; <sup>2</sup>University of California–Santa Barbara, ECE Dept., Santa Barbara, CA 93106 USA

Within the last decade, semiconductor microdisk resonators have become extremely useful for studying microcavity effects. A microdisk is a thin semiconductor disk surrounded by a lower index material such as air or SiO<sub>2</sub>. The large index difference between the semiconductor and the surrounding medium allows for strong optical confinement. The circular geometry of the disk permits low loss whispering gallery modes (WGMs) to propagate around the disk periphery through total internal reflection. The geometry of the microdisk is ideal for studying a material system such as GaN in which cleaved facets and several period epitaxial mirror stacks are problematic. Nonetheless, GaN microdisk development has been hindered by the inability to effectively surround the microdisk with lower index materials. Processing techniques, such as selective wet etching or oxidation, used for optical confinement of GaAs- and InP-based microdisks are not readily available for the GaN system because of its chemical stability. We must use unconventional processing techniques for GaN microdisk fabrication. One such technique is photoelectrochemical (PEC) etching. PEC etching uses above band gap illumination to generate the excess carriers (specifically holes) needed to etch GaN. Band bending near the material surface causes holes to be drawn toward the GaN-etchant interface, allowing them to participate in the electrochemical reaction necessary for material removal. Because the etching mechanisms rely heavily on the absorption of incident light, PEC etching is bandgap-selective. PEC etching has already demonstrated its utility in etching GaN. We have previously reported rapid, selective lateral etching resulting in the undercut or lift-off of GaN structures. Such etches exhibited finite selectivity and often resulted in rough etch surfaces. In order to fabricate high quality GaN microdisk structures, we must address these issues. In particular, the microdisk structure is extremely sensitive to surface roughness because it can cause scattering losses detrimental to optical performance. Furthermore, to prevent etching into the microdisk itself, we must increase the selectivity of the etch process. In these studies, we use an epitaxial structure grown by MOCVD which includes 1000 Å In<sub>0.12</sub>Ga<sub>0.88</sub>N sacrificial layer. Reactive ion etching is used to define micropillars of various diameters and expose the InGaN sacrificial layer. The GaN microdisks are undercut by using PEC etching to selectively etch the InGaN sacrificial layer. An optical filter is used to filter out light with energy greater than the bandgap of GaN. Thus, etching is prevented in the GaN layers and selective etching of the InGaN sacrificial layer occurs. The PEC etch conditions are optimized for lateral etch rates and smooth undercut surface. Although etch rates as high as 10 μm/min have been obtained, the smoothness of the undercut surface is our most critical parameter in our process. Photoluminescence measurements of the undercut microdisks confirm the disks are optically active. Our studies demonstrate the feasibility of using PEC etching as a means of fabricating high quality GaN microdisks.

**3:00 PM Break****3:20 PM**

**G6, Recombination Dynamics of Localized Excitons in Cubic In<sub>x</sub>Ga<sub>1-x</sub>N/GaN Multiple Quantum Wells on 3C-SiC/Si (001):** *Shigefusa Chichibu*<sup>1</sup>; Takeyoshi Onuma<sup>1</sup>; Toshio Kitamura<sup>2</sup>; Takayuki Sota<sup>3</sup>; Steven P. Denbaars<sup>4</sup>; Shuji Nakamura<sup>4</sup>; Hajime Okumura<sup>2</sup>; <sup>1</sup>University of Tsukuba, Inst. Appl. Phys., 1-1-1, Tsukuba, Ibaraki 305-8573 Japan; <sup>2</sup>AIST, Power Elect. 2, 1-1-1, Tsukuba, Ibaraki 305-8568 Japan; <sup>3</sup>Waseda University, EECE Dept., 3-4-1, Shinjuku, Tokyo 169-8555 Japan; <sup>4</sup>University of California, Matls. Dept., Santa Barbara, CA 93106 USA

Cubic (c-) GaN and related alloys are attracting attention since they are expected to have higher mobilities and higher activation of acceptors compared to their hexagonal (h-) polytype due to the higher crystal symmetry. Spontaneous emission efficiency of h-InGaN quantum-well (QW) light emitting diodes (LEDs) has been recognized to be controlled by a balance between the exciton localization and wavefunction separation due to quantum-confined Stark effect (QCSE), that is resulted from an electric field normal to the QW plane owing to spontaneous and piezoelectric polarizations. Since the latter degrades the efficiency with increasing InN mole fraction, it is difficult to obtain high efficiency

longer wavelength LEDs or cw laser diodes (LDs) to date. However, since the bandgap of c-GaN (3.22 eV) is approximately 0.2 eV smaller than that of h-GaN (3.42 eV) and c(001)-oriented cubic materials do not suffer from the field due to the polarization along the growth direction, c-InGaN is preferable to obtain pure blue or green LDs. Also, c-InGaN materials are interesting candidates to study an intrinsic localization effect excluding the modulation due to the polarization-induced field. In this study, recombination dynamics in a series of strained c-In<sub>x</sub>Ga<sub>1-x</sub>N/c-GaN MQWs having various well thickness and InN mole fractions were examined using temperature-dependent time-resolved photoluminescence (TRPL) spectroscopy. In contrast to h-InGaN QWs, low-excitation photoluminescence (PL) peak energy increased moderately with decreasing well thickness L and the PL lifetime did not strongly depend on L, the results clearly indicated that piezoelectric field was not acting on the transition process. The TRPL signals from the MQWs were well fitted by a model stretched-exponential decay from 10K to 300K, showing that the spontaneous emission is due to the radiative recombination of excitons localized in disordered quantum nanostructures such as In-clusters. The localized states were considered to have fractal dimensions with non-discrete density-of-states at 300K (quantum disk-size), since most of the InGaN LDs lase via electron-hole plasma process to date. This work has been supported in part by AOARD/AFOSR.

**3:40 PM**

**G7, Molecular-Beam Epitaxial Growth and Piezoelectric Investigation Under Applied Biaxial Stress of (In,Ga)N/GaN Multiple-Quantum Wells:** *Patrick Waltereit*<sup>1</sup>; Sung-Hwan Lim<sup>1</sup>; James S. Speck<sup>1</sup>; Michael D. Craven<sup>2</sup>; Steven P. Denbaars<sup>2</sup>; <sup>1</sup>University of California–Santa Barbara, Matls. Dept., Santa Barbara, CA 93106 USA; <sup>2</sup>University of California–Santa Barbara, Electl. Eng., Santa Barbara, CA 93106 USA

One of the most distinguishing properties of group-III nitrides are their polarization fields which, in the case of thin layers, lead to the quantum-confined Stark-effect (QCSE) that is accompanied by red-shifted transition energies in photoluminescence (PL). However, the actual magnitudes of the polarization fields are still under debate. In this work, we investigate the growth of (In,Ga)N/GaN multiple-quantum wells (MQWs) by plasma-assisted molecular-beam epitaxy on GaN(0001)/Al<sub>2</sub>O<sub>3</sub>(0001) templates and the dependence of the PL transition energies on applied biaxial tension (up to 0.0008). The samples are characterized by cross-sectional transmission-electron microscopy (TEM), high-resolution x-ray diffraction (HRXRD), atomic force microscopy (AFM) and room temperature PL. Deposition of the 13-period MQW structures was carried out at 580°C under metal-stable conditions for maintaining two-dimensional growth. Large In surface segregation present for (In,Ga)N growth requires considerably high In/Ga and V/III flux ratios and, thus, significantly lower Ga-fluxes during well than during barrier growth. Therefore, we employ two Ga sources with a flux ratio of about two. In the following, we investigate three samples grown under nominally identical conditions except for the In flux. The samples exhibit smooth surfaces with clearly visible atomic steps when observed by AFM. Excellent agreement of the experimental HRXRD profiles with dynamical diffraction simulations indicates smooth and uniform interfaces. The individual layer thicknesses for the wells (4.2 nm) and barriers (7.2 nm) and the In contents (2.5%, 8.5% and 11.9%) are thus extracted accurately. TEM confirms these thicknesses and also supports the high interface quality. Biaxial tension was applied to the samples employed as windows in a pressurized cell. The PL spectra were fitted for accurate determination of the peak energy. The PL energy shift with tension is composed of a red-shift ΔE<sub>g</sub> due to band-gap shrinkage and a competing blue-shift related to a reduced QCSE via the piezoelectric polarization PZ. A red-shift of 3 meV is observed for the smallest In content while a blue-shift of 6 meV is detected for the highest In content in qualitative agreement with self-consistent band profile calculations taking into account ΔE<sub>g</sub> and the reduced QCSE. However, the latter is well in excess of that conventionally calculated for (In,Ga)N/GaN MQWs. We attribute this observation to a substantial deviation of the experimentally determined piezoelectric polarization difference between In<sub>x</sub>Ga<sub>1-x</sub>N and GaN [ΔPZ(x,Δ̂)=-3.5\*x\*Δ̂ C/m<sup>2</sup>] under biaxial strain Δ̂ from that calculated for unstrained material [ΔPZ(x,Δ̂)=-0.6\*x\*Δ̂ C/m<sup>2</sup>]. This hypothesis is supported by recent calculations for biaxially strained (In,Ga)N layers [ΔPZ(x,Δ̂)=-1.8\*x\*Δ̂ C/m<sup>2</sup>]. The authors gratefully acknowledge N. A. Shapiro and E. R. Weber (UC Berkeley) for providing the strain-dependent PL data and useful discussions.

**4:00 PM Student**

**G8, Nonlinear Piezoelectric Effect in GaN/AlGa<sub>x</sub>N Quantum Wells:** *Georgiy Vaschenko*<sup>1</sup>; Dinesh Patel<sup>1</sup>; Carmen S. Menoni<sup>1</sup>; Hock M. Ng<sup>2</sup>; Alfred Y. Cho<sup>2</sup>; <sup>1</sup>Colorado State University, Dept. of Electl. & Compu. Eng., Ft. Collins, CO 80523 USA; <sup>2</sup>Lucent Technologies, Bell Labs., 600 Mountain Ave., Murray Hill, NJ 07974 USA

The polarization-induced electric field plays a major role in shaping the optical and electrical characteristics of the GaN/AlGa<sub>x</sub>N quantum well structures with wurtzite lattice. In the modeling of such structures it is commonly assumed that the macroscopic polarization has a linear strain dependence, with piezoelectric constants being the proportionality coefficients. Recent model calculations show that this is not the case, and that instead the polarization changes nonlinearly with strain<sup>1,2</sup>. We have shown that these nonlinearities are significant in InGa<sub>x</sub>N/GaN quantum wells<sup>3</sup>. In this contribution we investigate the GaN/AlGa<sub>x</sub>N system and provide experimental evidence of its nonlinear piezoelectric behavior, which is found to be on the scale comparable with model predictions. The GaN/AlGa<sub>x</sub>N structures for this work with AlN mole fraction in the barriers of  $x = 0.2, 0.5,$  and  $0.8$  and well widths ranging from  $1.5$  to  $4.5$ nm were grown on sapphire substrates by plasma-assisted molecular-beam epitaxy. To modify the strain in the GaN/AlGa<sub>x</sub>N quantum wells in a controllable way we use hydrostatic pressure. At each applied pressure we measure the steady state and time dependent photoluminescence (PL) from the quantum wells, which reflects changes in the bandgap and built-in electric field. In all studied samples we observe a significant variation of the pressure dependence of the PL peak energy with well width, and a significant increase of the PL lifetimes with pressure. Both of these effects result from an increase of the piezoelectric field with the strain generated by the pressure. Using the linear approximation of the elasticity theory we calculated the strain in the wells and in the barriers of the GaN/AlGa<sub>x</sub>N structures as a function of applied pressure. The bandgap energies were then calculated at each pressure using the deformation potentials of GaN and AlN, and accounting for excitonic effects. By comparing the results of these calculations with the measured PL peak energy we obtained the barrier-well polarization difference and therefore the total built-in electric field in the wells at each pressure. From this analysis we found that the field increases with applied pressure, the increase being much more significant in the experiment than that predicted by the linear model of polarization. In the sample with  $x = 0.5$  and  $2.5$ nm wide well the experimentally determined increase of the field in  $9$  GPa is  $1.12$  MV/cm, while the linear model predicts an increase of only  $0.34$  MV/cm. These experimental results will be compared with existing models of nonlinear polarization. <sup>1</sup>K. Shimada, et al, Jpn. J. Appl. Phys. 37, L1421 (1998); <sup>2</sup>F. Bernardini and F. Fiorentini, Phys. Rev. B64, 085207 (2001); <sup>3</sup>G. Vaschenko et al., Phys. Rev. B64, 241308 (2001).

**4:20 PM Student**

**G9, Piezoelectric Coefficients of III-V Wurtzite Nitrides:** *Philip Tavernier*<sup>1</sup>; Michael Boustie<sup>2</sup>; Jesse Williams<sup>1</sup>; David Clarke<sup>1</sup>; <sup>1</sup>University of California–Santa Barbara, Matls. Dept., Santa Barbara, CA 93106-5050 USA; <sup>2</sup>Laboratoire de Combustion et de Detonique, E.N.S.M.A., BP 109, Futuroscope, Cedex 86960 France

We have measured the piezoelectric coefficients of GaN and AlN using laser generated uniaxial strain waves to generate a strain-induced polarization charge. Our investigations have revealed that the sign of  $e_{33}$  in these materials is opposite to the sign of the theoretically calculated spontaneous polarization, contrary to case of zinc oxide. In order to support our findings, calibrations of the technique on single crystals of GaAs have been performed. The response from a (111A)GaAs wafer under an applied compressive stress generates a negative current swing; the opposite occurs when (111B)GaAs is stressed. We have also conducted studies on the extent to which free carrier screening in doped GaAs films decreases the piezoelectric response from the laser generated strain waves. The results indicate that films with free carrier concentrations of less than  $2 \times 10^{16}$  cm<sup>-2</sup> are sufficiently resistive to measure an accurate magnitude of the piezoelectric polarization for the stress rates ( $10^8$  GPa/s) presently used. At carrier concentrations higher than  $2 \times 10^{16}$  cm<sup>-2</sup> internal screening of the strain-induced charge reduces the observed short-circuit current magnitude. Numerical simulations based on SHYLAC hydrodynamic finite difference Lagrangian code have been used to model the applied pressure wave from the laser irradiation of GaAs, GaN on sapphire, and AlN on silicon. Agreement of the simulated pressure waves with those detected by laser Doppler interferometry have been used to

confirm the magnitude of the strain in these films. Having established and calibrated the technique, we have also analyzed GaN grown by HVPE and MBE. Convergent beam TEM studies are presently being used to affirm the surface polarity of HVPE GaN, Mg doped GaN films grown by MBE, and AlN films deposited by both MOCVD and RF sputtering and results of the measurement of the piezoelectric effect in these films will be presented. Additional investigations of the piezoelectric effect on both faces of single crystal ZnO will also be presented to describe examples of piezoelectric polarization in III-V zinc blende, III-V wurtzite, and II-VI wurtzite crystals.

**4:40 PM Student**

**G10, Polarization Bulk Doping in Graded AlGa<sub>x</sub>N Alloys:** *DebdEEP Jena*<sup>1</sup>; Sten Heikman<sup>1</sup>; Ilan B. Yaacov<sup>1</sup>; Robert Coffie<sup>1</sup>; James S. Speck<sup>2</sup>; Umesh K. Mishra<sup>1</sup>; <sup>1</sup>University of California–Santa Barbara, Dept. of Electl. & Compu. Eng., Santa Barbara, CA 93106 USA; <sup>2</sup>University of California–Santa Barbara, Matls. Dept., Santa Barbara, CA 93106 USA

By controlling the polarization charges in a graded AlGa<sub>x</sub>N layer, we demonstrate theoretically and experimentally the novel concept of polarization bulk doping in III-V nitride semiconductors. We achieve controlled n-doping without the introduction of donors. Transport measurements reveal the modulation doped nature of the free mobile carriers which most likely are provided by donor-like states at the AlGa<sub>x</sub>N surface, like in an Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN heterojunction. High density mobile two-dimensional electron gases (2<sup>o</sup>) form at undoped Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN heterojunctions to screen the *fixed* polarization sheet charge dipole in the AlGa<sub>x</sub>N layer. By linearly grading the Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN layer over a thickness, we spread the *fixed* polarization sheet charge into a uniform bulk charge. This bulk charge creates an electric field that extracts mobile charges from remote sources and creates a slab of mobile carriers. By linearly grading ‘up’, i.e., from GaN to Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN, we should achieve n-doping for Ga-face nitrides. The mobile carriers thus generated should exhibit improved mobility due to the absence of ionized impurities in the channel, and should not freeze-out at low temperatures owing to their ‘modulation doped’ origin. To verify these concepts, five samples were grown by molecular beam epitaxy (MBE). Active nitrogen was provided by a RF-plasma source. Semi-insulating GaN on sapphire grown by metal-organic chemical vapor deposition (MOCVD) were used as templates. For all five samples, a 100nm buffer MBE layer of undoped GaN was grown, followed by a different cap for each. The cap layer for the five samples were as follows-Sample 1) 100nm Bulk Si-doped GaN, Samples 2,3,4) 100nm 0-10,20,30% linearly graded AlGa<sub>x</sub>N, and Sample 5) 16nm 27% AlGa<sub>x</sub>N. X-Ray diffraction, SIMS, and AFM were performed on the five samples, showing good control of Al composition and layer thicknesses. Unintentional impurity incorporation was low, identical to the underlying MOCVD GaN template. Hall measurements were performed to measure the carrier concentrations and mobilities for all five samples at 300K and 77K. Temperature dependent Hall measurements from 20K-300K were also measured for the samples. Sample 1 showed the characteristic freeze-out associated with shallow donor doped carriers. Samples 2-4 showed no freeze-out, with effective bulk carrier density and mobility saturating at low temperatures. The measured mobility of the 3<sup>o</sup> is lower than 2<sup>o</sup>, and higher than donor doped structures of comparable carrier densities. This verifies our idea of polarization bulk doping. Carrier densities ranging from  $3-12 \times 10^{17}$  cm<sup>-3</sup>, 300K (77K) mobilities ranging from  $370-650(1500-2400)$  cm<sup>2</sup>/V.s was obtained for the graded AlGa<sub>x</sub>N layers. Sample 3 reached a high mobility of  $2580$  cm<sup>2</sup>/V.s at a charge of  $6 \times 10^{17}$  at 22K. Thus, we have demonstrated that polarization charges can be engineered to achieve bulk n-doping in graded AlGa<sub>x</sub>N layers with superior transport properties than donor-doped structures. The technique may be incorporated in device structures that require high carrier concentrations and high mobilities. In addition, the band offset can be used for hot electron launching at ohmic contacts. The technique can be extended by grading ‘down’ to get mobile holes; this might prove to be an attractive route to p-doping in the III-V nitride semiconductors.

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## Session H: Organic Semiconductors: Materials and Devices

Wednesday PM      Room: MultiCultural Theatre  
June 26, 2002      Location: University of California

*Session Chairs:* George Malliaras, Cornell University, Matl. Sci. & Eng., 306 Worth St., Ithaca NY 14853 USA; Hagen Klauk, Infineon Technologies AG, MP PMT, Postfach 32 20, Erlangen D-91050 Germany

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### 1:20 PM Invited

**H1, Carrier Heating in Molecular Crystals: Negative Differential Mobility in Pentacene:** *E. M. Conwell<sup>1</sup>; D. M. Basko<sup>1</sup>; <sup>1</sup>University of Rochester, Dept. of Chem., Rochester, NY 14627 USA*

It was first shown some time ago for naphthalene that highly purified single crystal specimens of molecular crystals have high enough mobility to show carrier heating effects at relatively low electric fields at low temperatures. It is well known that, for energies in the top part of an energy band, increase of energy results in a decrease of velocity, thus negative differential mobility, NDM, due to the increasing mass. For a narrow band with few carriers the carriers start out in the lower part of the band but, if it is possible to increase their energy sufficiently with an electric field to get them into the upper part of the band, further increase in the field and thus in their energy causes NDM. Measurements of drift velocity  $v_d$  vs. field  $E$  on highly purified single crystal naphthalene were first carried out by Warta and Karl. Using the time-of-flight method they found that  $v_d$  increases with  $E$ , linearly for low fields, then more slowly, and finally reaches a value which remains constant over a considerable range of fields. A similar saturation for pentacene was deduced from measurements of current density  $J$  vs. voltage  $V$  by Schon et al over a wide range of temperatures. Specifically, they used the relation for space-charge limited current,  $J_{SCLC} = (9/8) \epsilon \mu V^2/L^3$ , where  $L$  is the length of the sample, to determine the mobility  $\mu$  from the measured  $J$ ,  $V$ , and  $L$ . Drift velocity was then presumably obtained by multiplying  $\mu$  by  $V/L$ . However, the expression for  $J_{SCLC}$  is valid only when  $\mu$  is constant, thus only when  $v_d$  varies linearly with  $E$ . The procedure used by Schon et al. for determining  $\mu$  leads to the conclusion that in the saturation region  $J \propto V/L^2$  rather than  $V/L^3$ . In the absence of detailed knowledge about the coupling constants to acoustic and optical modes and the actual nonparabolicity of the valence band, it is not possible to do a rigorous calculation of  $v_d$  vs.  $E$  for holes in pentacene. We will show, however, by solving Poisson's equation, allowing for the carrier injection at the contact, that a typical variation of  $v_d$  with  $E$  having an NDM region leads to a saturation region for  $\mu V/L$ , as found in reference, and a linear increase of  $J$  with  $V$  in the saturation region in agreement with experiment.

### 2:00 PM

**H2, Transient Conductance in Organic Transistors:** *Robert Street<sup>1</sup>; Alberto Salleo<sup>1</sup>; Dietmar Knipp<sup>1</sup>; Armin Volkel<sup>1</sup>; <sup>1</sup>Palo Alto Research Center, Inc., 3333 Coyote Hill Rd., Palo Alto, CA 94304 USA*

Organic electronic materials are of great interest for large area electronics applications, and numerous materials are being studied, both small molecules and polymers. Our research is aimed at developing arrays of organic field effect transistors for active matrix displays and sensors. The performance of an organic transistor depends on many factors in addition to the carrier mobility of the material. These include the presence of traps in the semiconductor, the properties of the interface to the dielectric and the contacts to the source and drain electrodes. We report transient electrical measurements of the transistor characteristics to study these material effects. The transient response is also important for device performance. The materials studied include evaporated polycrystalline pentacene and spin-coated polyfluorenes and polythiophenes. When a transistor is turned on, current flows into the channel and the transient response reflects both the carrier mobility, and the ability of the contacts to supply the current. Figure 1 gives examples of turn-on transients for a polyfluorene transistor, at different gate voltages (up to -

20V) and with source-drain voltage at  $V_{DS}=0$ . The transients are studied for different channel lengths from 5 to 50 micron. The mobility and channel charge can be extracted from the data, and the long time decay reflects some limitation in the contacts that is confirmed by d.c. measurements. When the transistor is turned off, charge is released from the channel and flows to the contacts. The long time behavior reflects trapped charge in the channel and is observed as a slow response in both the polymers and in pentacene. Figure 2 shows data for polycrystalline pentacene, in which the current decay is observed over a time range of 10-7 to 10-2 sec. The slow response is attributed to the thermal excitation of charge from shallow acceptors in the pentacene near the dielectric interface, and the energy distribution extending from  $\sim 0.2$ - $0.5$ eV above the valence band is derived from the data, assuming a simple thermal excitation model. This distribution is in reasonable agreement with the results of a numerical model of the transistor, and is further evidence that transport in pentacene transistors is controlled by traps rather than grain boundary barriers.

### 2:20 PM

**H3, Organic Thin Film Transistors with Polymer Gate Dielectric Layer and Carrier Mobility of 0.5 cm<sup>2</sup>/V-s:** *Hagen Klauk<sup>1</sup>; Ute Zschieschang<sup>1</sup>; Marcus Halik<sup>1</sup>; Günter Schmid<sup>1</sup>; Wolfgang Radlik<sup>1</sup>; Werner Weber<sup>2</sup>; <sup>1</sup>Infineon Technologies, Polymer Matls. & Tech., Paul-Gossen-Str. 100, Erlangen 91052 Germany; <sup>2</sup>Infineon Technologies, Corporate Rsrch., Otto-Hahn-Ring 6, Munich 81730 Germany*

Pentacene organic thin film transistors (OTFTs) with high-quality inorganic gate dielectrics (such as ion-beam sputtered silicon dioxide and RF-sputtered aluminum oxide) have demonstrated electrical performance similar to or exceeding the performance of hydrogenated amorphous silicon TFTs, with carrier mobility greater than 1 cm<sup>2</sup>/V-s and single-stage propagation delay for ring oscillators of a few microseconds or less<sup>[1,2]</sup>. Spin-coated polymer gate dielectrics are of interest to simplify processing, reduce fabrication costs, and increase throughput, and OTFTs have been demonstrated with a variety of polymeric gate dielectric materials. The largest carrier mobilities reported for polymer gate dielectric OTFTs are around 0.5 cm<sup>2</sup>/V-s, obtained using bisbenzocyclobutene, polyimide, and parylene as the gate dielectric<sup>[3]</sup>. However, both bisbenzocyclobutene and polyimide are probably unsuitable for use with flexible polymeric substrates, since they typically require process temperatures of 200°C or higher. Parylene is deposited by vacuum vapor deposition and thus imposes similar throughput limitations as vapor-deposited inorganic gate dielectric materials. OTFTs have also been demonstrated with a variety of spin-coated, low-temperature polymeric gate dielectric materials, including polyvinylphenol, polymethylmethacrylate, novolac photoresists, and an organosilsesquioxane spin-on glass, but the largest carrier mobility reported for OTFTs with any of these spin-coated, low-temperature gate dielectric materials is only about 0.1 cm<sup>2</sup>/V-s<sup>[4]</sup>. We have fabricated pentacene OTFTs using spin-coated polyvinylphenol and its hydroxyethyl-methacrylate copolymer as the gate dielectric layer and obtained devices with carrier mobility as large as 0.5 cm<sup>2</sup>/V-s, on/off current ratio greater than 10<sup>4</sup>, and subthreshold slope around 1.5V/decade. Polyvinylphenol is soluble in a variety of organic solvents, is easily deposited by spin-coating (and possibly by spray-coating) to yield smooth films with low defect densities, can be cured at temperatures compatible with flexible polymeric substrates, and is characterized by large surface and volume resistivity. The permittivities of polyvinylphenol and its hydroxyethyl-methacrylate copolymer were determined from frequency-dependent impedance measurements. Pentacene OTFTs were fabricated using top-contact or bottom-contact device structures. In both cases, pentacene was deposited by thermal evaporation in vacuum, with substrates held at 60°C or at room temperature. Interestingly, the electrical TFT characteristics were found to be virtually identical for both device structures and for both deposition temperatures. Gate leakage through a 350nm thick gate dielectric film at a gate bias of 20 V is around 100 nA/cm<sup>2</sup>, comparable to the gate leakage through deposited inorganic gate dielectrics of similar thickness. <sup>1</sup>C. D. Sheraw et al., 2000 IEDM Techn Dig 619 2000; <sup>2</sup>J. H. Schön et al., Appl Phys Lett 79 4043 2001; <sup>3</sup>C. D. Sheraw et al., Mat Res Soc Symp Proc 558 399 2000; <sup>4</sup>J. A. Rogers et al., Proc NAS 98 4835 2001; H. Sirringhaus et al., MRS Bull 539 2001; G. H. Gelinck et al., Appl Phys Lett 77 1487 2000.

### 2:40 PM

**H4, Contact Resistance of OTFTs with Different Device Designs:** *David J. Gundlach<sup>1</sup>; Peter Necliudov<sup>2</sup>; Michael Shur<sup>2</sup>; Thomas N. Jackson<sup>1</sup>;*

<sup>1</sup>Pennsylvania State University, Dept. of Electl. Eng., University Park, PA 16802 USA; <sup>2</sup>Rensselaer Polytechnic Institute, ECSE, Troy, NY 12180 USA

We report on the contact resistance of organic thin film transistors (OTFTs) with different device designs. In recent years significant improvements have been made in device performance. Further progress requires a better understanding of non-ideal effects in these devices, such as the effect of large and, in many cases, nonlinear parasitic source and drain resistances. These resistances are especially important for shorter channel devices. Also, low frequency noise studies have shown that gate bias temperature stress primarily affects the contact regions. Only recently have contact effects and modeling of such effects for circuit applications received attention. In this work we fabricated pentacene OTFT test structures on oxidized silicon substrates using two OTFT designs: OTFTs with top or bottom source and drain contacts. Gold and palladium were used to form source and drain contacts. Top contact OTFTs were fabricated by depositing the source and drain contact metal through a shadow-mask onto the pentacene active layer while bottom contact OTFTs had source and drain contacts photolithographically-defined on the substrate prior to depositing the active layer. Contact resistance was extracted from linear regime current-voltage characteristics of OTFTs with different channel length,  $L$ , and constant channel width, using a gated transmission line model pattern. The magnitude of the contact resistance and the change in resistance as a function of gate and drain-source voltages was found to be different for top and bottom contact devices. For both structures however, the extracted contact resistance is large and exceeds the intrinsic channel resistance for OTFTs with channel length less than  $30\mu\text{m}$ . Such contact resistance strongly limits the extrinsic saturation and linear region field-effect mobility. We find that after correcting for contact resistance the intrinsic field-effect mobility in the linear regime is largely channel length independent and ranges from  $0.55$  to  $0.8\text{ cm}^2/\text{V}\cdot\text{s}$ ; an order of magnitude larger than the extracted extrinsic mobility of short channel length devices ( $L < 5\mu\text{m}$ ). Our results show that reducing contact resistance is of great importance for improving OTFT performance.

### 3:00 PM Break

### 3:20 PM

**H5, Functionalized Acenes for Improved Electronic Properties:** *John E. Anthony*<sup>1</sup>; David L. Eaton<sup>1</sup>; Marcia Payne<sup>1</sup>; <sup>1</sup>University of Kentucky, Dept. of Chem., Lexington, KY 40506-0055 USA

The emergence of organic semiconductors as viable components for electronic devices has brought about a realization of the importance of solid-state order. High mobilities are predicated on efficient  $\pi$ -overlap between adjacent molecules throughout the solid, a state which most aromatics, with strong preference to edge-to-face interactions, would prefer not to adopt. We have undertaken a project to prepare substituted pentacenes, in order to determine whether the solid-state morphology can be controlled in a systematic way. We have developed a general scheme for such functionalization, which leads to pentacenes crystallizing in three basic ways: As slip-stacked columns, as linearly-stacked columns, and as two-dimensional sheets. The electronic properties of these new morphologies of pentacene show significant conductivity anisotropy (2-4 orders of magnitude), and resistivities along the most conductive axis ranges from  $10^8$  to  $10^6\text{ ohm}\cdot\text{cm}$ . Thermal conductivity band gaps measured for these crystals range from  $0.5\text{ eV}$  along the most conductive crystalline axis, to  $>2\text{ eV}$  along the most insulating. Band structure calculations based on the crystallographic data supports these observations, with significant dispersion observed along the most conductive ( $\pi$ -stacking) axis of the crystal. Although evaporation of these pentacene derivatives leads to nearly amorphous thin films of low conductivity, exposure of these films to vapors of organic solvents leads to instantaneous crystallization, with a concomitant increase in the conductivity of the annealed film by several orders of magnitude. SEM analysis of these films show microcrystalline structure, with grain sizes on the order of  $900\text{nm}$ . These films show remarkable oxidative stability—sample films exposed to air and sunlight for several weeks showed no appreciable degradation after analysis. The high solubility of these compounds makes them amenable to spin-casting, and preliminary photovoltaic devices have been prepared on plastic substrates by this technique. Approaches to pentacene compounds substituted to enhance the formation of self-assembled monolayers, as well as the preparation of larger acenes (e.g. heptacene) will be discussed.

### 3:40 PM Student

**H6, Designing Organic Semiconductors: A Case Study Using Quinoid Oligo-thiophenes:** *Reid J. Chesterfield*<sup>1</sup>; Ted M. Pappenfus<sup>2</sup>; Kent R. Mann<sup>2</sup>; Larry L. Miller<sup>2</sup>; C. D. Frisbie<sup>1</sup>; <sup>1</sup>University of Minnesota, Cheml. Eng. & Matls. Sci., 421 Washington Ave. SE, Minneapolis, MN 55455 USA; <sup>2</sup>University of Minnesota, Chem., 207 7th St. SE, Minneapolis, MN 55455 USA

Solution processable organic semiconductors are an exciting new class of materials because of the prospect for realizing inexpensive and flexible, large-area thin film transistor (TFT) arrays. The authors present a family of soluble n-channel materials based on quinoid terthiophene derivatives, which illustrate the elegance of using organic chemistry techniques to design semiconductor materials. One compound in this family, 3',4'-dibutyl-5,5''-bis(dicyanomethylene)-5,5''-dihydro-2,2':5,2''-terthiophene (DCMT) has a room temperature n-channel TFT mobility of  $0.01$  and  $0.003\text{ cm}^2/\text{Vs}$  in vacuum evaporated and solution cast films, respectively. By varying the end groups, alkyl side-chain length, and number of thiophene rings we can determine what types of solid-state interactions control the molecular packing, and hence electrical properties. The base molecule of this family, terthiophene, has previously shown only p-channel TFT behavior. Cyclic voltammetry of DCMT showed reversible oxidation ( $E^0 = -0.17\text{ V}$ ) and reduction ( $E^0 = +1.27\text{ V}$ ); whereas, terthiophene shows only reversible reduction. This illustrates how electrochemistry can be used to design organic semiconductors for TFTs. Another important consideration in semiconductor design is molecular packing in the crystal structure. Single crystals of DCMT exhibit slipped  $\pi$ -stacking in the solid state with an intermolecular face-to-face stacking length of  $3.47\text{ \AA}$ . Thin films rarely pack the same as single crystals; however,  $\pi$ -stacking in the single crystal structure suggested the possibility for high thin film mobilities, as observed in DCMT TFTs. Thin film morphology was investigated using atomic force microscopy (AFM) and x-ray diffractometry (XRD). AFM micrographs of DCMT films showed high crystallinity and grains as large as  $10\mu\text{m}$ . Since grain boundaries are a well-known source of electrical traps, transport measurements were taken as a function of temperature and under controlled atmosphere, in order to study the carrier activation energy as a function of grain boundary environment. Also important for thin film structure and mobility is the type of substrate dielectric used (aluminum oxide versus silicon oxide), and so experiments were performed to investigate substrate influence. By systematically varying the molecular structure in this family of organic semiconductors we present a case study for designing these materials using the powerful techniques available in organic chemistry. The ultimate goal is a soluble, air-stable, and high mobility ambipolar material, which may be achievable in this family of organic semiconductors.

### 4:00 PM Student

**H7, Organic Thin Film Transistors Based on Functionalized Pentacene Active Layers:** *Chris D. Sheraw*<sup>1</sup>; Thomas N. Jackson<sup>1</sup>; David L. Eaton<sup>2</sup>; John E. Anthony<sup>2</sup>; <sup>1</sup>The Pennsylvania State University, Dept. of Electl. Eng., 121 EE E., University Park, PA 16802 USA; <sup>2</sup>University of Kentucky, Dept. of Chem., 027 Chem.-Phys. Bldg., Lexington, KY 40506 USA

Organic thin film transistors (OTFTs) are of interest for a variety of low-cost, large-area electronic applications such as RF identification tags and flexible flat panel displays. To date, the OTFTs with highest reported performance have been based on single crystals<sup>1</sup> and thin-films<sup>2</sup> of pentacene, with field-effect mobility  $> 2\text{ cm}^2/\text{V}\cdot\text{s}$ . We report here on OTFTs fabricated using pentacene functionalized to improve molecular ordering and material stability, and to allow solubility in common organic solvents<sup>3</sup>. Previous work on pentacene derivatives used functionalized pentacene as a soluble precursor to fabricate solution-cast unsubstituted pentacene OTFTs<sup>4</sup>. While pentacene has been used to fabricate devices with high mobility, the ordering of unsubstituted pentacene molecules consists of a combination of edge-to-face and face-to-face arrangements that results in minimal  $\delta$ -orbital overlap. To increase  $\delta$ -overlap, bulky groups were substituted at the *peri* positions of the molecule with a rigid alkyne spacer. This substitution discourages edge-to-face interactions and can give molecular crystals with only face-to-face interactions, with a significant increase in  $\delta$ -stacking and the potential for improved carrier mobility. The functionalization of these pentacene materials also increases the oxidative stability of the molecule and allows the molecule to be readily dissolved in common organic solvents. For example, X-ray crystallography reveals that triisopropylsilylethynyl pentacene (TIPS Pc) does indeed stack in a two-dimensional columnar

array with significant  $\delta$ -orbital overlap and reduced interplanar spacing compared to unsubstituted pentacene. TIPS, trimethylsilyl (TMS), *t*-Butyl, and Hexyl functionalized pentacene OTFTs were fabricated using a heavily doped silicon wafer as the substrate and gate electrode. A layer of thermally grown silicon dioxide (330nm thick) was used as the gate dielectric. A 50nm average thickness active layer was deposited by thermal evaporation at  $\sim 0.5 \text{ \AA}/\text{sec}$  with a system pressure of  $10^{-7}$  torr, and gold source and drain contacts were evaporated through a shadow mask. OTFTs were fabricated with and without treatment of the gate dielectric surface with octadecyltrichlorosilane (OTS) prior to active layer deposition. OTFTs fabricated with TIPS Pc deposited onto untreated substrates held at  $90^\circ\text{C}$  had field-effect mobility near  $10^{-4} \text{ cm}^2/\text{V}\cdot\text{s}$ . TIPS Pc OTFTs fabricated identically except with OTS-treated gate dielectric had field-effect mobility as large as  $10^{-2} \text{ cm}^2/\text{V}\cdot\text{s}$  and on/off current ratio  $> 10^5$ . These results demonstrate that OTFTs with good performance and the possibility of improved stability and simplified processing can be fabricated using functionalized pentacene derivatives. <sup>1</sup>J. H. Schon, *Synth. Met.* 122, 157 (2001); <sup>2</sup>D. J. Gundlach, et. al., *57th DRC Technical Digest*, 164 (1999); <sup>3</sup>J. E. Anthony, et. al., *J. Am. Chem. Soc.*, 123, 9482 (2001); <sup>4</sup>P. T. Herwig, et. al., *Adv. Mat.*, 11, 480 (1999).

#### 4:20 PM

**H8, Charge Injection in Organic Semiconductors:** Yulong Shen<sup>1</sup>; Daniel Jacobs<sup>1</sup>; David Dulap<sup>1</sup>; *George G. Malliaras*<sup>1</sup>; <sup>1</sup>Cornell University, Dept. of Matls. Sci. & Eng., 327 Bard Hall, Ithaca, NY 14853-1501 USA

Knowing how the current at the contacts depends on material parameters is of fundamental importance for the understanding and optimization of organic optoelectronic devices such as light emitting diodes and transistors. We have measured the electrical characteristics of various contacts between commonly used anode electrodes (such as ITO and Au) and various hole transport layers, including N-N'-diphenyl-NN'-bis(3-methylphenyl)-1-1-biphenyl-4,4'-diamine (TPD) and poly[2-methoxy,5-(2-ethylhexoxy)-1,4-phenylene vinylene] (MEH-PPV). By carrying out independent measurements of the hole mobility in the organic layers we are able to isolate the injection and the transport processes and study the electrical characteristics of the contact alone. We find that most of the commonly used contacts in organic light emitting diodes are in fact not Ohmic, but current-limiting. The injected current is found to have a similar electric field dependence as the space charge limited current. Surprisingly, the injected current scales with the hole mobility in the organic, which was varied in the range of  $10^{-6}$  and  $10^{-3} \text{ cm}^2/\text{V}\cdot\text{sec}$  by diluting TPD into polycarbonate. We show that this unexpected result is due to the hopping nature of transport in the organic material. We demonstrate ways to improve injection by modifying the contact by thin metallic layers and implement these modified contacts in organic light emitting diodes. A mechanism for this improvement is proposed.

#### 4:40 PM

**H9, Late News**

## Session I: Special Topical Session: Semiconductor Spintronics - I

Wednesday PM Room: UCEN State Street  
June 26, 2002 Location: University of California

*Session Chairs:* Chris Palmström, University of Minnesota, Cheml. Eng. & Matls. Sci., 421 Washington Ave. SE, Minneapolis, MN 55455 USA; Scott Chambers, Pacific Northwest National Laboratory, Fundamental Sci. Div., PO Box 999, MS K8-93 Richland, WA 99352 USA

#### 1:20 PM Student

**I1, Growth and Magnetic Properties of Digital Ferromagnetic Heterostructures Prepared by Atomic Layer Epitaxy:** *Ezekiel Johnston-Halperin*<sup>1</sup>; T. C. Kreuz<sup>1</sup>; J. Schuller<sup>1</sup>; R. K. Kawakami<sup>1</sup>; E. G. Gwinn<sup>1</sup>; A. C. Gossard<sup>1</sup>; D. D. Awschalom<sup>1</sup>; <sup>1</sup>University of California-Santa Barbara, Ctr. for Spintronics & Quantum Computation, iQUEST, Santa Barbara, CA 93106 USA

Molecular beam epitaxy growth of ferromagnetic semiconductors is of interest due to the flexibility heteroepitaxy affords both in integration with current III-V semiconductor technology and in atomic-scale spin engineering. One example of this flexibility in the development of digital ferromagnetic heterostructures (DFH), wherein single MnAs layers, 0.5 monolayers (ML) in thickness, are periodically inserted into a GaAs matrix<sup>1</sup>. These superlattices are shown to exhibit both inter- and intra-layer ferromagnetic interactions, with the intra-layer coupling sufficient to generate ferromagnetic order in isolated 0.5 ML MnAs layers. One disadvantage of this growth technique, which also plagues the random alloy (Ga,Mn)As, is that the low substrate temperature (typically  $250^\circ\text{C}$  to  $300^\circ\text{C}$ ) necessary to prevent MnAs cluster formation also results in the inclusion of excess As in the form of anti-site defects<sup>2</sup>. These anti-sites serve as deep traps for the holes introduced by the Mn, which have been shown to participate in free-carrier mediated ferromagnetism in (Ga,Mn)As<sup>3</sup>, and therefore may act to limit the maximum attainable Curie temperature,  $T_C$ . In an attempt to control this incorporation we employ atomic layer epitaxy (ALE), a growth mode wherein each atomic layer is deposited independently and sequentially, allowing precise control of the stoichiometry. We find that ALE DFH structures can be grown at substrate temperatures from  $175^\circ\text{C}$  to  $230^\circ\text{C}$  by varying the ALE algorithm. Superconducting quantum interference device (SQUID) magnetometry of these ALE structures does not reveal an increase in  $T_C$  commensurate with the decrease in As incorporation, but does show distinct hysteretic behavior suggesting the activation of an additional magnetic phase. Support for this work is provided by DARPA, ONR, and AFOSR. <sup>1</sup>R. K. Kawakami, E. Johnston-Halperin, L. F. Chen, M. Hanson, N. Guébels, J. S. Speck, A. C. Gossard, and D. D. Awschalom, *Appl. Phys. Lett.* 77 2379 (2000); <sup>2</sup>M. Kaminska, Z. Liliental-Weber, E. R. Weber, T. George, J. B. Kortright, F. W. Smith, B-Y. Tsaur, and A. R. Calawa, *Appl. Phys. Lett.* 54, 1881 (1989); <sup>3</sup>H. Ohno, *Science* 281, 951 (1998), and references therein.

#### 1:40 PM Invited

**I2, Ab-Initio Transport in Digital Ferromagnetic Heterostructures:** *Stefano Sanvito*<sup>1</sup>; <sup>1</sup>Trinity College Dublin, Dept. of Physics, Dublin 2, Ireland

Digital ferromagnetic heterostructures are MnAs/GaAs superlattices made by delta-doping GaAs with Mn. Here we present a theoretical study of the electronic, and transport properties of such heterostructures. The calculations are based on density functional theory in the local spin density approximation, and our numerical implementation uses pseudopotentials and localized atomic orbital basis set. We address the following questions: i) what is the real dimensionality of the system? ii) are the carriers spin-polarized? iii) what is the carrier distribution in the system? In the absence of intrinsic donors the system shows a half metallic density of states. The exchange interaction is much stronger than that of a random alloy with the same Mn concentration, and it is almost independent of the separation between the MnAs layers. This suggests that indeed the carriers responsible for the ferromagnetism are strongly confined in the MnAs planes. We then perform ab-initio ballistic transport calculations to gain insight into the spatial distribution of the carriers. We generalize a well established quantum transport Green's functions technique, to the case of a density functional derived Hamiltonian. In the specific case the matrix elements of the Hamiltonian and overlap matrix are evaluated by numerical integration over a grid. Our results show that the carriers with energies close to the Fermi energy are strongly confined within a few monolayers of the MnAs plane. The ballistic conductance of carriers at the Fermi energy is strongly anisotropic, with the conductance in the MnAs plane one order of magnitude larger than that in the direction perpendicular to the planes. If As antisites are present the situation is rather different. An As antisite introduces an impurity level in the band gap, destroying the half-metallic band structure. However, because of the strong confining potential when the As antisites are not in the MnAs planes, there is also a charge separation. This results in fully polarized holes in the MnAs plane, and un-polarized electrons in the GaAs spacer. In conclusion, ab initio ballistic transport calculations show that undoped digital ferromagnetic heterostructures behave as two dimensional metals, with metallic conductance in the MnAs plane and tunneling like conductance in the perpendicular direction. If As antisites are present charge separation will occur, and the half-metallic behavior in the MnAs planes will be maintained.

## 2:20 PM Student

**I3, Transport and Magnetic Studies of Digital (Ga,Mn)As Heterostructures: Spacer Dependence, Growth Temperature Dependence and Carrier Concentrations:** *T. C. Kreuzt<sup>1</sup>; W. Allen<sup>1</sup>; G. Zanelatto<sup>1</sup>; E. G. Gwinn<sup>1</sup>;* <sup>1</sup>University of California–Santa Barbara, Dept. of Physics, Santa Barbara, CA 93106 USA

Digital ferromagnetic heterostructures (DFH) are superlattices in which 1/2 monolayer (ML) MnAs planes alternate with undoped GaAs spacer layers. In this study, we examine the relationship between transport and magnetic properties as a function of the spacer layer thickness. By examining the longitudinal resistance, and treating the DFH superlattice as a parallel resistor network, we observe two regimes. For large spacer thickness, the longitudinal resistance scales as the inverse of the total number of layers in the DFH. For small spacer thickness the resistance is less than would be expected from a parallel resistor model. This suggests an inter-layer electronic coupling that is activated as the layers approach each other. Further, if we examine the Curie temperature of these materials as a function of spacer thickness, we see that  $T_C$  is constant at large spacer thickness and is enhanced for thinner spacers.<sup>1</sup> This is consistent with a decoupling of the layers magnetic properties and roughly coincides with the electronic decoupling, suggesting that the free carriers potentially play an important role in the inter-layer ferromagnetism. <sup>1</sup>R. K. Kawakami, E. Johnston-Halperin, L. F. Chen, M. Hanson, N. Guebels, J. S. Speck, A. C. Gossard and D. D. Awschalom, *Appl. Phys Lett* 77, 2379 (2000).

## 2:40 PM

**I4, Effects of Disorder and Frustration on Ferromagnetism in Diluted Magnetic Semiconductors:** *Ravindra N. Bhatt<sup>1</sup>; Malcolm P. Kennett<sup>2</sup>; Mona Berciu<sup>3</sup>; Xin Wan<sup>4</sup>;* <sup>1</sup>Princeton University, Electl. Eng., Eng. Quad., Princeton, NJ 08544 USA; <sup>2</sup>Princeton University, Physics Dept., Jadwin Hall, Princeton, NJ 08544 USA; <sup>3</sup>Princeton University, Princeton Matls. Inst., Bowen Hall, Princeton, NJ 08540-5211 USA; <sup>4</sup>Florida State University, Natl. High Magnetic Field Lab. & Physics Dept., 315 Keen Bldg., Tallahassee, FL 32306 USA

We compare the results of a variety of phenomenological models for diluted magnetic semiconductors, based on microscopic models appropriate for different regimes of carrier densities and local moment concentrations. These include models that are spin only, as well as models involving both spin and charge carrier (fermionic) degrees of freedom. In the low charge carrier and local moment concentration regime, we examine a model for III-V diluted magnetic semiconductors such as (Ga,Mn)As, based on an impurity band built from Mn acceptor wavefunctions, in which the charge carriers are coupled to the magnetic ions. We have studied the properties of this model using mean field and Monte Carlo techniques, and used it to motivate a phenomenological, spin only, two-component model which provides an adequate description of thermodynamic properties such as magnetization, specific heat and magnetic susceptibility. While the model is most appropriate for the insulating phase, some of its features are expected to be observed into the metallic regime. The nature of the ferromagnetic phase below the critical temperature is found to be rather unusual: the local magnetization exhibits strong spatial fluctuations, which are correlated with fluctuations in the local charge carrier density induced by the positional disorder of the dopant. The magnetization curves as well as the hysteresis curves in the ferromagnetic phase are found to be unusual as well. We show that this also results in unconventional spin excitations, and correspondingly unconventional thermodynamic properties. We have also studied a model appropriate at higher doping levels, which takes into account the effects of spin-orbit coupling, present in hole doped DMS. We include both disorder and frustration coming from spin-orbit coupling to examine their effects on the low temperature ordered phase. We present results for several thermodynamic quantities, such as the linear and non-linear magnetic response in both the ferromagnetic and paramagnetic phases, as well as hysteresis curves in the ordered phase. We analyze the role of the positional disorder, as well as that of anisotropy in the spin interactions on the nature of the ordered phase. We examine various experimentally accessible quantities in different cases, in an effort to untangle the different effects that are present in actual diluted magnetic semiconductor systems. The implications of both disorder and frustration for spin transport and scattering are explored.

## 3:00 PM Break

## 3:20 PM Invited

**I5, Correlation of the Mn Lattice Location, Free Hole Concentration and Curie Temperature in Ferromagnetic GaMnAs:** *Kin Man Yu<sup>1</sup>;* <sup>1</sup>Lawrence Berkeley National Laboratory, Matls. Scis. Div., Berkeley Lab., One Cyclotron Rd., MS2-200, Berkeley, CA 94720 USA

Mn atoms incorporated into ferromagnetic  $Ga_{1-x}Mn_xAs$  can occupy three distinct types of lattice site: substitutional positions in the Ga sublattice, where  $Mn^{2+}$  ions act as acceptors and contribute to uncompensated spins; interstitial positions, where they act as donors and tend to passivate substitutional Mn acceptors; and random locations, when Mn precipitates as another phase, e.g., in the form of MnAs inclusions. In order to understand the limitations on the maximum Curie temperature  $T_C$  in  $Ga_{1-x}Mn_xAs$  grown by low temperature molecular beam epitaxy, it is essential to address the issue of the lattice site location of Mn atoms in the alloy. In this work we investigated the relationships between the lattice location of Mn atoms with the free hole concentration, the saturated magnetization, and the Curie temperature of  $Ga_{1-x}Mn_xAs$  thin films. We have found a strong correlation between the location of Mn sites in  $Ga_{1-x}Mn_xAs$  and its Curie temperature. Using channeling Rutherford backscattering and particle induced x-ray emission we have identified interstitial Mn atoms in as-grown  $Ga_{1-x}Mn_xAs$  alloy films, and we observed that these interstitials transformed to random precipitates (e.g., MnAs inclusions) when the film was annealed at 282°C, only slightly higher than the growth temperature (265°C). In particular, we noticed that the Curie temperature of  $Ga_{1-x}Mn_xAs$  is clearly affected by the rearrangement of the Mn atoms in the crystal lattice. The concentrations of free holes determined by electrochemical capacitance-voltage profiling and of uncompensated  $Mn^{2+}$  spins determined from SQUID magnetization measurements are also found to depend on the concentration of the Mn interstitials. It should be noted that the Mn interstitials are naturally unstable and highly mobile. The relationship of  $T_C$  to the behavior of Mn interstitials thus leads to wide variations of this parameter for annealing even in a narrow temperature window. The fact that annealing under various conditions has failed to produce Curie temperatures above ~110K can be attributed to the existence of an upper limit on the free hole concentration in low-temperature-grown  $Ga_{1-x}Mn_xAs$ . The effects on the Mn site location and the Curie temperature by introducing additional acceptors such as Be during  $Ga_{1-x}Mn_xAs$  growth have also been investigated, and the results will be discussed.

## 4:00 PM Student

**I6, Ferromagnetic  $Ga_{1-x}Mn_xAs$  and  $Ga_{1-x}Mn_xAs_{1-y}C_y$  Produced by Ion Implantation and Laser Annealing:** *Michael A. Scarpulla<sup>1</sup>; Kin M. Yu<sup>2</sup>; Manoj R. Pillai<sup>3</sup>; Mark C. Ridgway<sup>4</sup>; Michael J. Aziz<sup>2</sup>; Oscar D. Dubon<sup>1</sup>;* <sup>1</sup>University of California–Berkeley, Dept. of Matls. Sci. & Eng., 577 Evans Hall, Berkeley, CA 94720 USA; <sup>2</sup>Lawrence Berkeley National Laboratory, Matls. Sci. Div., 1 Cyclotron Rd., Berkeley, CA 94720 USA; <sup>3</sup>Harvard University, Div. of Eng. & Appl. Scis., McKay 504, Cambridge, MA 02138 USA; <sup>4</sup>Australian National University, Rsrch. Sch. of Physl. Scis. & Eng., Dept. of Elect. Matls. Eng., Canberra, Australia 2617 Australia

It has been demonstrated<sup>1</sup> that conventional semiconductors can be transformed into dilute magnetic semiconductors (DMSs) by the introduction of magnetic impurities. However, as these species typically have extremely low solubilities in III-IV and elemental semiconductors, synthesizing such materials presents many challenges. In order to incorporate magnetic impurities at concentrations of a few atomic percent, processing must take place far from equilibrium. For example, GaAs doped with the magnetic impurity Mn must be grown by low-temperature molecular beam epitaxy ( $T < 300^\circ C$ ) to prevent Mn segregation and the formation of Mn-based second phases. Yet exceedingly low temperatures ( $T < 200^\circ C$ ) can lead to films of poor structural quality, containing a high density of electrically active point defects. Despite such experimental challenges,  $Ga_{1-x}Mn_xAs$  has received considerable attention due to its novel magnetic properties including ferromagnetism above liquid nitrogen temperatures. One alternative process for synthesizing heavily-doped semiconductors is ion implantation followed by pulsed laser melting (PLM). In this method, a substrate is implanted to the desired concentration and exposed to high-energy laser pulses which induce recrystallization. Successful incorporation of impurities to atomic percent levels has been demonstrated for several materials systems including As-doped Si<sup>2</sup> and Te-doped GaAs<sup>3</sup>. We present a study of the structural, electrical, and magnetic properties of thin  $Ga_{1-x}Mn_xAs$  films formed by Mn implantation into GaAs and subsequent PLM. The films are shown to be highly crys-

talline and to exhibit ferromagnetic behavior. Preliminary measurements indicate that the ferromagnetic behavior of the films is due to substitutionally incorporated Mn. We have also investigated the effects of co-doping in this system using carbon, which is normally an acceptor in GaAs residing on the As sublattice. We find that these  $\text{Ga}_{1-x}\text{Mn}_x\text{As}_{1-y}\text{C}_y$  films exhibit similar magnetic properties to those produced without C. <sup>1</sup>H. Ohno, Science 281, 951 (1998); <sup>2</sup>D. Nobili, A. Carabelas, G. Celotti, and S. Solmi, J. Electrochem. Soc. 130, 922 (1983); <sup>3</sup>J. A. Golovchenko and T. N.C. Venkatesan, Appl. Phys. Lett. 32, 147 (1978).

#### 4:20 PM

**17, Electronic Structure and Spin-Polarization of MnGaN:** *Leor Kronik*<sup>1</sup>; Manish Jain<sup>1</sup>; James R. Chelikowsky<sup>1</sup>; <sup>1</sup>University of Minnesota, Cheml. Eng. & Matls. Sci., 421 Washington Ave. SE, Minneapolis, MN 55455 USA

Over the last few years, significant strides in growth and processing technology have made MnGaAs the dilute magnetic semiconductor of choice. However, the Curie temperature of MnGaAs is well below room temperature. Dietl et al. predicted theoretically, based on a Zener model, that a MnGaN alloy, with an amount of Mn comparable to that used in MnGaAs, should result in a significantly elevated Curie temperature. This has led to a flurry of experimental activity, culminating in reports of ferromagnetic MnGaN with a Curie temperature above or close to room temperature. A successful operation of spintronic devices also requires, however, that one may inject spin-polarized charge carriers into a non-magnetic semiconductor. Here, we examine the theoretical limits to spin-polarized transport in wurtzite  $\text{Mn}_x\text{Ga}_{1-x}\text{N}$ , with a realistic value of  $x=0.063$ . We examine the ideally ordered, ferromagnetic phase of this alloy using first principles calculations based on pseudopotentials within spin-polarized density functional theory. By calculating the density of states (DOS), we find that the introduction of Mn results in the formation of a Mn-related, ideally spin-polarized impurity-band that is  $\sim 1.5$  eV wide. A partial DOS analysis reveals that the impurity band is due to a broadening of the discrete Mn 3d impurity level, via hybridization with N 2p orbitals. By calculating the band structure, we find that the alloy remains a direct band-gap semiconductor, but this semiconductor now contains a spin-polarized impurity band that features a significant dispersion along some directions of the Brillouin zone. With the Fermi level lying within this impurity band, we find that  $\text{Mn}_{0.063}\text{Ga}_{0.937}\text{N}$  is an ideal half-metal. This means that 100% spin-polarized carrier injection may proceed by simple effective-mass transport through the impurity band. Therefore, we predict that if technological barriers can be overcome, MnGaN is preferable to MnGaAs not only because of its potentially higher Curie temperature, but also because its band structure is inherently much more suitable for spintronics applications.

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18, Late News

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## Session J: Antimonide-Based Materials & Devices - II

Wednesday PM      Room: UCEN Harbor  
June 26, 2002      Location: University of California

*Session Chairs:* Ishwara Bhat, Rensselaer Polytechnic Institute, Elect. Compu. & Sys. Eng. Dept., 110 8th St., Troy, NY 12180-3590 USA; & Robert Biefeld, Sandia National Laboratories, Dept. 1113, MS 0601, PO Box 5800, Albuquerque, NM 87185-0601 USA

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#### 1:20 PM

**J1, Anion Exchange Reactions and Isoelectronic AsSb Formation:  $\text{GaSb}_y\text{As}_{1-y}/\text{GaAs}$  and  $\text{GaAs}_y\text{Sb}_{1-y}/\text{GaSb}$  Superlattice Interface Quality:** *Maria Losurdo*<sup>1</sup>; Giovanni Bruno<sup>1</sup>; Terence Brown<sup>2</sup>; April S. Brown<sup>2</sup>; Gary May<sup>2</sup>; <sup>1</sup>Istituto di Metodologie Inorganiche e dei Plasmi, IMIP-CNR, via Orabona, 4, Bari 70126 Italy; <sup>2</sup>Georgia Institute of Technology, Sch. of Electl. & Compu. Eng., Microelect. Rsrch. Ctr., 791 Atlantic Dr., Atlanta, GA 30332 USA

The investigation of III-V anion exchange reactions at heterojunction interfaces is of fundamental interest. As an example, there is current great interest in antimonide/arsenide heterostructures for specific device applications, such as infrared photodetectors, lasers, and HBTs. The performance of these devices is strongly influenced by the composition, microstructure, and thickness of the heterointerfaces. Abrupt and atomically smooth interfaces require the control of the anion exchange. Because of the critical dependence of the electronic and optical properties of the SL on the thickness and composition of individual layers as well as of interfaces, nondestructive techniques with atomic-level resolution are required. Furthermore, very few non-destructive techniques allow quantitative measurement of the As/Sb anion interface segregation. Spectroscopic ellipsometry (SE) is a monolayer-sensitive interface technique that can be applied to the non-destructive compositional/microstructural analysis of SLs. In this contribution,  $\text{GaAs}_y\text{Sb}_{1-y}/\text{GaSb}$  and  $\text{GaSb}_y\text{As}_{1-y}/\text{GaAs}$  SLs grown by MBE, respectively, by exposure of GaAs to a Sb flux and by exposure of GaSb to an As flux have been investigated by SE, covering the 1.5-5.5 eV photon energies. The SLs pseudodielectric function has been measured, and the analysis gives information on the quality and composition of interfaces in the SLs and layer thickness at with Angstrom resolution. Complementary information on the composition of layers and abruptness of interfaces has been obtained by XPS. The data show that the As-for-Sb anion exchange reaction occurs into the GaSb surface layer to large extent. However, this anion exchange results in the formation not only of a ternary alloy  $\text{GaAs}_y\text{Sb}_{1-y}$ , but also in the formation of isoelectronic compounds  $\text{AsSb}_x$  that segregate at the GaSb/As interface. The As-for-Sb anion exchange reaction competes with the AsSb formation. The AsSb segregation can be explained by the large diffusion length of As and the low out-diffusion coefficient of Sb, and precludes the formation of abrupt  $\text{GaAs}_y\text{Sb}_{1-y}/\text{GaSb}$  interface. Nevertheless, the Sb segregation, that acts as a sink for As, further inhibits As diffusion into the GaSb. The relative number of Ga-As bonds, i.e., the "y" value in  $\text{GaAs}_y\text{Sb}_{1-y}$ , and of the AsSb formation depends on surface temperature and As flux exposure time. In contrast, when a GaAs layer is exposed to an Sb flux, the Sb segregates at the GaAs surface, and the Sb-for-As anion exchange reaction does not occur into the underlying GaAs layers. The fate of the Sb monolayer during the SL growth depends on the growth temperature. We present studies as a function of surface temperature and Sb/As flux exposure time that reveal the chemical mechanism controlling the anion exchange reaction in both  $\text{GaAs}_y\text{Sb}_{1-y}/\text{GaSb}$  and  $\text{GaSb}_y\text{As}_{1-y}/\text{GaAs}$  systems. A chemical-kinetic model that takes into account the competitive formation of isoelectronic AsSb compound (neglected in the conventional thermodynamic and kinetic models) is proposed. The authors gratefully acknowledge the support of the Air Force Research Laboratory (F3361598C5428).

#### 1:40 PM Student

**J2, Characterization of Anion Exchange for Mixed Group V Heterostructures During Molecular Beam Epitaxy:** *Terence Brown*<sup>1</sup>; Gary May<sup>1</sup>; April S. Brown<sup>1</sup>; <sup>1</sup>Georgia Institute of Technology, Electl. & Compu. Eng., 791 Atlantic Dr., Atlanta, GA 30332 USA

The electronic properties of many compound semiconductor devices are highly dependent on heterointerface structure and composition. In recent years, mixed anion materials have become the focus of interest for designing next-generation devices such as long-wavelength lasers and high-frequency HEMTs and HBTs. While these materials offer significant advantages in the form of band gap engineering, a better understanding of the processes occurring during the growth of the interfaces will allow for improvements in device performance and manufacturing. We have used high-resolution x-ray diffraction to characterize and compare the exchange process at the interfaces of mixed anion heterostructures. Superlattices (SLs) formed by the exposure of GaAs surfaces to  $\text{Sb}_2$  and the exposure of GaSb surfaces to  $\text{As}_2$  and  $\text{As}_4$  were grown by molecular beam epitaxy and characterized. Interface composition profiles were obtained from kinematical simulations performed on the structures that exhibited anion exchange. The focus of this work is the characterization and modeling of the anion exchange process. Structural and compositional information obtained from spectroscopic ellipsometry (SE) and x-ray photoelectron spectroscopy (XPS) are used in conjunction with the x-ray simulation data to resolve the interface profiles. These experiments consist of 20-period  $\text{GaAs}_y\text{Sb}_{1-y}/\text{GaSb}$  and  $\text{GaSb}_y\text{As}_{1-y}/\text{GaAs}$  SLs grown with no cap layer, such that the final interface is exposed for chemical analysis by XPS. Conditions such as substrate temperature and anion



exposure time were varied to impact the degree of exchange. Kinematical simulations of As<sub>4</sub>-exposed GaSb material revealed distinct structures for various As exposure times. Both SE spectra and XPS results indicate that the exchange reaction occurs to a different extent and through different mechanisms for this set of structures. Simulations for structures with 10s As exposure times were achieved by the modeling of exchanged layers. These structures consisted of a uniform intermixed layer of one or more MLs of material at the interfaces. X-ray simulations for structures with exposure times of 30s revealed structures with extensive intermixing of As within GaSb. The results obtained via XPS indicate that the impinging As anion diffuses into the GaSb underlayers. Simulations of As<sub>2</sub>-exposed GaSb exhibit a greater degree of diffusion, resulting in an extensive As-for-Sb exchange process and strain relaxation. Modeling of As diffused GaSb layers proceeded by inserting linear composition variations at the interfaces. The exchanged Sb population is believed to segregate up through the lattice toward the interface where AsSb<sub>x</sub> compounds are formed, preventing further As diffusion. The simulations for Sb<sub>2</sub>-exposed GaAs consisted of both exchanged layers and layers containing segregation, a decaying compositional profile toward the sample surface. Segregation modeling was accomplished using exponential composition variations at the interfaces. Analysis performed on SE spectra reveals that the Sb-for-As exchange reaction does not occur.

## 2:00 PM

**J3, Surfactant Effects on the Nucleation of InAsSb Semiconductor Nanostructures:** *Jeff Cederberg*<sup>1</sup>; S. R. Kurtz<sup>1</sup>; R. M. Biefeld<sup>1</sup>; <sup>1</sup>Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185 USA

We have made the unexpected observation of a "surfactant" effect for the formation of III-V nanostructures. The addition of antimony to InAs, forming a dilute alloy InAs(Sb), results in dramatic transformations of the nanostructures formed. In a complementary experiment, As is added to InSb to form a dilute alloy In(As)Sb, which also dramatically changes the island size and density distributions. The growth of semiconductor nanostructures by CVD requires understanding of the initial nucleation of deposits. Using reactor growth studies coupled with ex situ sample analysis by Atomic Force Microscopy (AFM), we have conducted a detailed investigation of these two different material systems: InAs on GaAs(001) and InSb on GaSb(001). These films are predicted to nucleate by the Stranski-Krastanov (SK) mechanism, forming nanometer-sized islands in a two-dimensional wetting layer. The strong surfactant effect is a surprise. Small (35 x 20nm, 2nm high), dense (300 μm<sup>-2</sup>) islands are formed for 9 Å-thick InAs grown on GaAs(001), that are elongated towards the [1-10] direction. The addition of antimony results in the coalescence of small islands into long, wire-like structures that are elongated in the perpendicular direction, i.e., in the [110] direction. Isolated islands can be formed for the InAs(Sb) alloy by decreasing the deposit thickness to 7.5 Å. The islands thus formed are larger than InAs structures, and are still elongated in the [110] direction. Looking at the complementary case of InSb on GaSb(001), we see formation of very large (140 x 40nm, 2nm high) islands under all conditions investigated. The addition of As to form In(As)Sb produces smaller (50 x 20nm, 1nm high), dense (90 μm<sup>-2</sup>) islands. The alloyed structures are smaller than the pure InSb islands grown under the same conditions. InAsSb islands on GaAs and GaSb exhibit PL from 980nm to 1.7 μm, respectively. Clearly the minority constituent has a sharp impact on the mechanism of island nucleation. Our proposed explanation is due to the weaker bonding of antimony compared to arsenic. The addition of antimony to an arsenic-terminated surface may increase the diffusion length of adatoms and decrease the surface energy. Conversely, the addition of arsenic to antimony-terminated surfaces may decrease the diffusion length and increase the surface energy.

## 2:20 PM Student

**J4, Self Assembled Quantum Wires in GaAs/GaSb Short Period Superlattices:** *Catalina I. Dorin*<sup>1</sup>; Corinna Wauchop<sup>2</sup>; Joanna Mirecki Millunchick<sup>1</sup>; <sup>1</sup>University of Michigan, Matls. Sci. & Eng., Ann Arbor, MI 48109 USA; <sup>2</sup>University of Michigan, Electron Microbeam Analysis Lab., Ann Arbor, MI 48109 USA

One common method for obtaining nanometer-sized features is by taking advantage of the Stranski Krastanov nucleation mode to self-assemble quantum dots. An alternative approach is by the deposition of short period superlattices (SPS), where each layer is on the order of one or two monolayers (ML) thick. Such structures have been shown to possess significant and periodic compositional modulations (CM) in the

plane of the film, and have been exploited in device structures based on nanometer scale features. The work reported to date has been on mixed cation systems such as AlAs/InAs, GaAs/InAs or GaP/InP. In this paper, we demonstrate for the first time lateral composition modulation in GaAs/GaSb SPS. Cross sectional transmission electron diffraction (XTEM) and X-ray diffraction (XRD) show that lateral CM occurs for structures deposited at T = 400C and a total group V pressure of 10<sup>-5</sup> torr where the thickness of the GaSb layer is nominally 2 ML and GaAs layer is 1 or 2 ML. (002) High Angle Annular Dark Field image (HAADF) of this sample shows image contrast that is due only to compositional variations in the film. The Sb composition x in the Sb-rich and As-rich regions as were determined from the X-ray Energy Dispersive Spectroscopy (XEDS) line profile is x Sb = 0.77 and x As = 0.33. The wavelength is  $\bar{E} = 23\text{nm}$ . Increasing the thickness of the GaAs layer to 2 ML introduced significant roughening during growth, thus destroying the regularity of the CM regions. XTEM images suggest that the microstructure consists of vertically stacked islands. In an attempt to improve the interfacial abruptness, another GaAs<sub>2</sub>ML/GaSb<sub>2</sub>ML SPS was deposited with an additional 4-second Sb soak prior to deposition of GaSb layer. HAADF for this sample demonstrates that the lateral CM is regular and periodic, but slightly tilted away from the surface normal due to the presence of steps at the interface. XEDS for this sample shows that x Sb = 0.73, x As = 0.33 and  $\bar{E} = 15\text{nm}$ . The composition modulation observed in these films is a result of the SPS growth and not due to spinodal decomposition, as evidenced by the fact that alloys grown in the same conditions results in homogeneous layers. The HAADF and XEDS measurements for these alloy films, indicate that there is little As incorporation. It was also found that As segregation is significant in both alloys and SPS structures, and it is likely to play an important role in the mechanism driving lateral composition modulation.

## 2:40 PM Student

**J5, Identification of Type I Offset Behavior in AlInAsSb/InAsSb MQW Structures:** *Leslie Vaughn*<sup>1</sup>; L. Ralph Dawson<sup>1</sup>; Edwin Pease<sup>1</sup>; Luke F. Lester<sup>1</sup>; <sup>1</sup>University of New Mexico, Ctr. for High Tech. Matls., 1313 Goddard St. SE, Albuquerque, NM 87106 USA

Until recently, the dominant materials system used for mid-infrared semiconductor lasers have been limited to Type II bandgap structures. The demonstration of stable MBE growth of AlInAsSb quaternary alloys using a digital alloy method allows exploration of AlInAsSb/InAsSb MQW structures for aluminum composition well into the predicted miscibility gap. Photoluminescence (PL) measurements for structures in this materials system suggest that it has a nested bandgap structure and varying the composition of the well material, while introducing more compressive strain, has led to longer wavelengths. Al<sub>(0.3)</sub>In<sub>(0.7)</sub>As<sub>(x)</sub>Sb<sub>(1-x)</sub> alloys, known to well within the miscibility gap for essentially all values of x, were grown by MBE using the digital alloy technique, and used as the barrier material in a multiple quantum well (MQW) structure. This structure, grown on GaSb substrates, has lattice-matched barriers and compressively strained InAsSb well as determined by XRD. Using an experimentally confirmed quaternary bandgap model and Type I band offsets taking into account strain, the wavelengths for InAsSb wells with 0.3 to 1.1% strain are predicted to be 3.58 to 4.12 microns at room temperature. We have observed consistent PL peak wavelengths of 3.25 microns at 90K in 0.3% strained wells, which translates to a room temperature wavelength of about 3.46 microns. Structures with 1.1% strain result in 3.97 microns at 99K, or 4.17 microns equivalent for room temperature. The good agreement of these experimental results with the theoretical model indicates that the AlInAsSb/InAsSb material system is one of the few Type I quantum wells having demonstrated light emission in the technologically important mid-IR band from 3.3 to 4.2 microns. The results are very promising for the use of these heterojunctions in mid-IR semiconductor lasers.

## 3:00 PM Break

## 3:20 PM

**J6, The Preparation of InGa(As)Sb & Al(Ga)AsSb Films & Diodes on GaSb for Thermophotovoltaic Applications Using Metal-Organic Chemical Vapor Deposition:** *Jeff Cederberg*<sup>1</sup>; M. A. Hafich<sup>1</sup>; R. M. Biefeld<sup>1</sup>; M. Palmisiano<sup>1</sup>; <sup>1</sup>Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185 USA

We are exploring Al(Ga)AsSb and InGaAsSb alloys lattice matched to GaSb for use in series thermophotovoltaic (TPV) applications. We have investigated the growth and doping of these quaternaries using metal-

organic chemical vapor deposition (MOCVD) in vertical high-speed rotating disk reactors. For AlGaSb, the growth rate is not a linear combination of the binary alloy growth rates. Pre-reactions impact alloy growth rate and solid-vapor distribution. We have characterized the effect of growth parameters on carbon and oxygen concentrations in Al(Ga)(As)Sb. Background oxygen is reduced at higher growth rates, while carbon increases; increasing the V/III lowers background carbon. Improvements in background impurity levels have allowed us to demonstrate Al(Ga)AsSb diodes with reverse breakdown voltages  $> 10$  V. InGa(As)Sb with a bandgap of 0.60 eV has been routinely grown. We have determined that temperatures  $< 550^\circ\text{C}$  are necessary to grow material with bandgaps below 0.60 eV. TPV diodes have been grown and characterized. This work was supported by Bechtel Bettis. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Department of Energy under contract DE-AC04-94AL85000.

### 3:40 PM

**J7, Reduction of the Interface Recombination Rate in GaInAsSb/GaSb Broken-Gap Heterostructures:** *Dmitri Donetsky<sup>1</sup>*; Christine A. Wang<sup>2</sup>; Sergey Anikeev<sup>1</sup>; Gregory Belenky<sup>1</sup>; Serge Luryi<sup>1</sup>; <sup>1</sup>State University of New York at Stony Brook, Light Eng. Bldg., ECE Dept., Stony Brook, NY 11794-2350 USA; <sup>2</sup>Massachusetts Institute of Technology, Lincoln Lab., 244 Wood St., Lexington, MA 02420-9108 USA

Recently, high-performance thermophotovoltaic (TPV) devices based on 0.53-eV GaInAsSb were demonstrated. It was reported that a higher energy gap window layer was critical for reducing the surface recombination velocity, although no measurements of recombination lifetimes were made. In fact, there are very few recombination lifetime studies for the GaInAsSb materials. This paper reports electron lifetimes in p-GaSb/p-GaInAsSb/p-GaSb and p-AlGaAsSb/p-GaInAsSb/p-AlGaAsSb double heterostructures (DH's) that were specially grown to investigate the effects of confining layers on surface recombination velocity (SRV). It is shown that the use of heavily doped p-GaSb confining layers significantly reduces the recombination rate at broken-gap (type-II) heterointerfaces, while the valence band lineup at the p-GaInAsSb/p-AlGaAsSb interface is the most effective in reducing SRV. The GaInAsSb heterostructures consisted of a p-GaInAsSb active narrow-gap (0.53-0.55 eV) layer and either p-GaSb (0.72 eV) or p-AlGaAsSb (1 eV) confining layers. All heterostructures were grown lattice matched to n-GaSb substrates by organometallic vapor phase epitaxy at growth temperatures of  $525^\circ\text{C}$  for GaInAsSb,  $550^\circ\text{C}$  for AlGaAsSb, and  $525$  or  $550^\circ\text{C}$  for GaSb. The GaInAsSb layer thickness was varied from 1.2 to 5  $\mu\text{m}$  and was p-doped with Zn at  $2 \times 10^{17} \text{ cm}^{-3}$ . The GaSb confining layers were 50nm thick and were either nominally undoped ( $p=1 \times 10^{16} \text{ cm}^{-3}$ ) or p-doped with Zn at  $2 \times 10^{18} \text{ cm}^{-3}$ . The AlGaAsSb confining layers were 50nm thick and nominally undoped p-type at  $2 \times 10^{17} \text{ cm}^{-3}$ . For structures with AlGaAsSb confining layers, a 2.5-nm-thick p-GaSb layer was grown after the first AlGaAsSb confining layer and after the GaInAsSb layer. This thin GaSb layer stabilizes the epitaxial surface during interruptions used for growth temperature changes. Previously, the lack of high-sensitivity, high-speed detectors for the energy gap of interest precluded the use of time-resolved photoluminescence (PL) measurements. Lifetimes in earlier reports were indirectly determined by radio-frequency photoreflectance. In the present work PL decays were measured by an HgCdTe photodiode with a resolution of 5 ns. The bulk lifetime and SRV were separated using data on samples with different thickness assuming negligible photon recycling. The structures with undoped p-GaSb confining layers have the highest SRV of 3100 cm/s. With the heavily doped p-GaSb confining layers, SRV is reduced by a factor of 2.7 to 1140 cm/s. The smallest SRV of 720 cm/s is obtained for DH's with AlGaAsSb confining layers. These observations can be explained by the p-type broken-gap heterointerface. The accumulation of electrons at the interface will be responsible for an increased recombination rate. Calculations performed for p-GaSb/p-GaInAsSb interface have shown that heavily doped p-GaSb can compensate the band bending effect to achieve near flat-band conditions. Thus, the recombination rate for electrons will be effectively suppressed. In the case of AlGaAsSb confining layers, there is no valence band offset and the observed SRV is slightly smaller compared to the DH with heavily p-doped GaSb.

### 4:00 PM

**J8, Comparing Pseudopotential Predictions for InAs/GaSb Superlattices:** *Gregory Dente<sup>1</sup>*; Michael Tilton<sup>2</sup>; Andrew Ongstad<sup>3</sup>; Ron Kaspi<sup>3</sup>; <sup>1</sup>GCD Associates, Rsrch. Dept., 2100 Alvarado NE, Albuquerque, NM

87110 USA; <sup>2</sup>Boeing Defense & Space Group, RTS, PO Box 5670, Albuquerque, NM 87185 USA; <sup>3</sup>Air Force Research Laboratory, Tactical Laserers Grp., AFRL/DELS, Albuquerque, NM 87117-5776 USA

The widely used theoretical method for calculating the electronic and optical properties of superlattice materials is based on k.p perturbation theory and the envelope function approximation. Indeed, this "effective mass" approach has been used so extensively that it has been referred to as the Standard Model. Unfortunately, although the Standard Model has considerable intuitive appeal, the theoretical underpinnings for heterostructure applications remain controversial. Pseudopotential techniques have often been suggested as more accurate alternatives to the Standard Model. The most commonly employed model forms the pseudopotential for the superlattice as a superposition of atomic pseudopotentials; we refer to this as the "atomistic" EPM. In contrast, an alternative superlattice pseudopotential solution method, the SEPM requires an EPM description of the bulk component materials, and then, using only the energy-band lineups or offsets between component materials, fuses the bulk-like layer potentials into the pseudopotential for the superlattice. The critical SEPM assumption is that the heterointerface charges redistribute, forming charge and dipole sheets near the interface, in order that the layer pseudopotentials remain as bulk-like as possible. This assumption, in turn, allows us to form the pseudopotential for the superlattice, while only introducing an offset parameter for each pair of materials in the superlattice. This SEPM superlattice pseudopotential construction is quite different from those based on a superposition of atomic pseudopotentials. In the atomistic EPM approaches, one arrives at the pseudopotential for the superlattice by superimposing potentials for each ion site in the superlattice. For InAs/GaSb superlattices, this construction requires, at the minimum, functional pseudopotential fits for "In in As", "As in In", "Ga in Sb" and "Sb in Ga". However, the atomistic EPM approach would appear sound and complete, allowing for microscopic detail such as the inclusion of interfacial segregation and intermixing. In this presentation, we will make a detailed comparison of the atomistic EPM and the SEPM. In particular, we will compare predictions for FTIR absorption spectroscopy results. Two sets of InAs/GaSb Type-II superlattice samples, with thirty periods each, were grown and characterized. In one set of five samples, the InAs layer thickness, per period, was fixed at 6 monolayers (ML), while the GaSb layer thickness was nominally 6, 9, 12, 18 and 24 ML per period. In the second set of six samples, the InAs layer thickness, per period, was 8 ML, while the GaSb layer thickness was nominally 8, 12, 16, 24, 32, and 40 ML. In these comparisons, we will show that the SEPM provides far better agreement with the measured data.

### 4:20 PM Student

**J9, Chlorine Doping in ZnMgSe: Theory and Experiment:** *Brenda Vanmil<sup>1</sup>*; Yaxiang Yang<sup>1</sup>; Craig H. Swartz<sup>2</sup>; Leonid Muratov<sup>1</sup>; Bernard R. Cooper<sup>1</sup>; Thomas H. Myers<sup>1</sup>; <sup>1</sup>West Virginia University, Physics, PO Box 6315, Morgantown, WV 26506-6315 USA

The wide-band-gap semiconductor ZnSe and its alloy  $\text{Zn}_x\text{Mg}_{1-x}\text{Se}$  continue to be of interest because of potential electro-optic applications. This materials system can be used for devices operating in the blue to ultraviolet spectral region. By increasing the Mg content, the band gap of  $\text{Zn}_x\text{Mg}_{1-x}\text{Se}$  can be modified from 2.7eV for pure ZnSe to approximately 3.7eV for MgSe. Chlorine, as the most successful n-type dopant for ZnSe, is considered a candidate for n-type doping in ZnMgSe. Experimental results to date, however, have been disappointing. To gain an understanding of the issues involved, ZnSe and ZnMgSe chlorine doped epitaxial layers were grown for comparison to predictions made with computational modeling to investigate Cl solubility, native defects and chlorine-impurity-related defects. We used the ab-initio full potential LMTO method to model native defects and chlorine-impurity-related defects in ZnSe and  $\text{Zn}_x\text{Mg}_{1-x}\text{Se}$ , and focused on the changes in the electronic properties with increase of Mg content. The addition of Mg reduces the formation energy for chlorine on the Se site, predicting an enhanced Cl incorporation that was verified by experiment. Our theoretical results also show that there is a strong tendency for formation of a defect complex between the chlorine impurity at the Se site and a vacancy at the neighboring Zn site. In ZnSe, this allows quantitative comparison between predicted and measured lattice constants based on our defect model. The formation energies of this complex and other chlorine related defects again decrease in the presence of magnesium. While this defect complex will serve as a compensating center, the maximum achiev-

able electron concentration in the presence of magnesium is actually lower because of the increase in the band gap. Our theoretical results quite accurately predict the maximum achievable electron concentration obtainable as a function of Mg concentration. Finally, experimental trends in carrier concentration indicate an enhanced probability for native defect formation at high Cl flux. This is shown to be the result of competition between growth and Cl flux for Zn atoms, resulting in a decrease in growth rate and a concomitant increase in Zn vacancy formation. We show how growth conditions can be modified to overcome this effect.

#### 4:40 PM

**J10, High Mobility and 9.5 Micron Cut-Off Wavelength InAsSb Films Grown on Semi-Insulating GaAs by Liquid Phase Epitaxy:** V. K. Dixit<sup>1</sup>; Bhavtosh Bansal<sup>1</sup>; V. Venkataraman<sup>1</sup>; H. L. Bhat<sup>1</sup>; <sup>1</sup>Indian Institute of Science, Dept. of Physics, Bangalore, Karnataka 560012 India

InAs<sub>x</sub>Sb<sub>(1-x)</sub> alloy has the lowest energy gap among all the III-V semiconducting compounds and their alloys. This reduction in InSb's gap on alloying has important technological implications in infrared red (IR) detector applications. For use in IR detectors, it is best to grow epitaxial films of the active material on an IR transparent and electrically insulating substrates. Semi-insulating GaAs, in spite of a large 14% lattice mismatch with InAs<sub>x</sub>Sb<sub>(1-x)</sub>, has proved to be most relevant because it is known to yield tolerable interfaces and satisfies the above two criteria. Such films on GaAs substrates, so far have been grown only by non-equilibrium techniques like MBE and MOCVD. This is the first report of liquid phase epitaxy (LPE) growth of InAs<sub>x</sub>Sb<sub>(1-x)</sub> films on GaAs substrates. This we believe is an important breakthrough, since LPE is an old and established technique for industrial production. The quality of the films grown was comparable to the best grown on GaAs substrates by other methods. Epitaxial films of InAs<sub>x</sub>Sb<sub>(1-x)</sub> on (001) semi-insulating GaAs substrate could be grown, up to x=0.06. They were grown in a boat-slider LPE unit. Following a procedure similar to the one previously used by us to grow InSb/GaAs, the growth was carried out at 442°C using an indium rich InAsSb solution. InAs<sub>x</sub>Sb<sub>(1-x)</sub>/GaAs samples, with x=0.04 and x=0.06 were studied. SEM micrographs revealed that the interface was abrupt. XRD showed the epilayers had the substrate orientation and a smaller lattice parameter, than InSb. Arsenic composition was determined by energy dispersive x-ray analysis and cross checked with the XRD data, through Vegard's law. From the Fourier transform infrared transmission spectra, recorded at room temperature, a minimum energy gap of 0.13eV was obtained for films with x=0.06. This corresponds to 9.5µm and hence is well within the 8-12µm atmospheric window, important for IR detectors. Conductivity and Hall coefficient were measured between 10K and 370K for films with x=0.04 and x=0.06. The samples were n-type in the entire temperature range. The room temperature electron mobility and carrier concentrations in both the samples were ~ 3.5x10<sup>4</sup> cm<sup>2</sup>/V.s and 5x10<sup>16</sup> cm<sup>-3</sup> respectively. These values of electron mobility obtained here are one the highest obtained for the InAsSb/GaAs system.

## Session K: Materials Integration: Wafer Bonding and Alternative Substrates - II

Wednesday PM Room: UCEN Flying A  
June 26, 2002 Location: University of California

*Session Chair:* Karl Hobart, Naval Research Laboratory, 4555 Overlook Ave., Washington, DC 20375 USA

#### 1:20 PM Student

**K1, Wafer Bonding for III-V on Insulator Structures:** S. Hayashi<sup>1</sup>; D. Bruno<sup>1</sup>; R. Sandhu<sup>1</sup>; M. S. Goorsky<sup>1</sup>; <sup>1</sup>University of California, Dept of Matls. Sci. & Eng., Los Angeles, CA 90095 USA

To demonstrate the feasibility of creating III-V on insulator structures, InP and GaAs layers were bonded to GaAs wafers using a silicon nitride intermediate layer. GaAs-GaAs bonding is employed to determine whether defects are caused that are not related to differences in thermal expansion coefficients. InP-GaAs structures offer a test structure that can be compared directly to standard InP substrates. Both structures

are precursors to the transfer of large lattice parameter layers whose substrates do not exhibit semi-insulating behavior. Key process parameters in the formation of these structures include the silicon nitride surface roughness and density as produced by plasma-enhanced chemical vapor deposition (at different temperatures) and deposition by sputtering. Smooth silicon nitride layers were obtained without chem-mech polishing (r.m.s. roughness < 0.45nm, as determined using atomic force microscopy and x-ray reflectivity). The surfaces were sufficiently smooth such that, when coupled with an oxygen plasma treatment (200 mtorr, 200W, 60s) produced nitride/nitride interfacial bond strengths that appear to exceed the fracture limits of GaAs and InP. Hydrogen implantation was also included to split off InP layers from a bulk InP substrate. X-ray diffraction measurements showed that the implant introduced a highly strained layer near the surface. The strained region relaxed upon subsequent annealing along with the introduction of tilted regions that are introduced by the agglomeration of hydrogen. Based on these findings, x-ray scattering was found to be a very useful technique to monitor the kinetics of the hydrogen-induced blistering and subsequent layer transfer. The strain in the InP layer after transfer to the GaAs substrate was determined using x-ray reciprocal space mapping; transfer of a GaAs layer to a separate GaAs substrate showed no strain or any other signs of processing-induced defects in the transferred layer, as confirmed with transmission electron microscopy measurements.

#### 1:40 PM

**K2, Wafer Bonded InP/Si and InP/Ge for 4-Junction Solar Cell Heterostructures:** James Zahler<sup>1</sup>; Anna Fontcuberta Morral<sup>2</sup>; Harry A. Atwater<sup>2</sup>; <sup>1</sup>California Institute of Technology, Cheml. Eng., 1200 E. California Blvd., Pasadena, CA 91125 USA; <sup>2</sup>California Institute of Technology, Thomas J. Watson Lab. of Appl. Physics, 1200 E. California Blvd., MS 128-95, Pasadena, CA 91125 USA

The integration of dissimilar materials is a key issue in the future design and fabrication of optoelectronic devices. Ion implantation-induced layer transfer processes have enabled the transfer of large-area silicon films and the possibility of extensive substrate re-use. Recently, this method has been successfully applied to Ge<sup>1</sup>, but less work has been done for III-V semiconductors. Here we present the results on the bonding and layer transfer of InP onto Si and Ge, and application to the fabrication of GaInP<sub>2</sub>/GaAs/InGaAsP/InGaAs four junction solar cell heterostructures<sup>2</sup> in which the InP transferred layer serves as an epitaxial template for MOCVD growth of the bottom cell InGaAs/InGaAsP double heterostructure, and a thin GaAs template layer bonded on top serves as a template for growth of a second GaInP<sub>2</sub>/GaAs double heterostructure. Thin film InP/Si and InP/Ge heterostructures have been fabricated by direct wafer bonding of H + and He + -implanted (100) InP to hydrogen-terminated Si (100) and Ge (100) substrates. Atomic force microscopy measurements indicate that high dose H + and He + implantation did not increase the InP surface roughness (rms roughness < 0.5 nm). To minimize particle contamination of the InP bonding surface, photoresist was spun onto the wafers before being cleaved into 1 cm x 2 samples that were cleaned and whose surfaces were rendered hydrophobic by a HF dip. The wafers were bonded at room temperature and annealed under uniaxial pressure to induce layer splitting. Figure 1 shows a 0.7 µm thick (100) InP transferred layer on Si (100). Atomic force microscopy indicates an rms roughness of the transferred layer of 10nm. The total transferred area is several mm<sup>2</sup>. The borders show some waviness, in which initial debonding is attributed to the stress produced by the difference in coefficient of thermal expansion of InP and Si. Similar results for InP/Ge, which are better thermally matched, (CTE of Ge is 5.8 10<sup>-6</sup>, 2.6 10<sup>-6</sup> for Si and 5.8 10<sup>-6</sup> for InP) will be reported, as will be InP/Si interfacial I-V characteristics and photoluminescence and lifetime characterization of MOCVD-grown InGaAs/InP and InGaAsP/InGaAs/InP bonded to Si and Ge substrates. <sup>1</sup>Zahler, J., et al., Ge Layer Transfer To Si For Photovoltaic Appl. Thin Solid Films, 2001 (submitted). <sup>2</sup>Sharps, P. et al., Wafer bonding for use in mechanically stacked multi-bandgap cells, in 26th. IEEE Photovoltaic Specialists Conference 1997. Anaheim, CA: IEEE Press.

#### 2:00 PM

**K3, Wafer Bonded Ge/Si Substrates for Triple Junction Solar Cell Structures:** James M. Zahler<sup>1</sup>; Chang-Geun Ahn<sup>1</sup>; Harry A. Atwater<sup>1</sup>; Charlie Chu<sup>2</sup>; Peter Iles<sup>2</sup>; <sup>1</sup>California Institute of Technology, Thomas J. Watson Lab. of Appl. Physics, 1200 E. California Blvd., Pasadena, CA 91125 USA; <sup>2</sup>TECSTAR/ASD, 15251 Don Julian Rd., City of Industry, CA 91745 USA

Materials integration of lattice mismatched semiconductors via direct hydrophobic wafer bonding and layer transfer has many potential applications for photovoltaics design and manufacture. Specifically, by utilizing hydrophobic wafer bonding and layer transfer to fabricate Ge/Si substrates consisting of a thin layer of Ge on a bulk Si substrate with ohmic interfacial electrical properties, triple junction solar cells can be grown on a low cost, mechanically robust Si substrate. Thin film Ge/Si heterostructures have been fabricated by implanting (100)Ge substrates with H<sup>+</sup> at 80keV to a dose of  $1 \times 10^{17} \text{ cm}^{-2}$ . Prior to bonding both the Ge and Si substrates are cleaved into  $\sim 1 \text{ cm}^2$  samples and cleaned to remove particulates and render the surface hydrophobic with less than 0.5nm rms roughness as measured by atomic force microscopy. The wafers were then bonded at room temperature and annealed to  $>350^\circ\text{C}$  to induce layer splitting producing a  $\sim 700 \text{ nm}$  thick layer of Ge on Si with an as-cleaved surface roughness of 10-20nm rms. Optical characterization of triple junction GaInP/GaAs/Ge solar cells grown by MOCVD on the as cleaved Ge surface ( $\sim 20 \text{ nm}$  rms roughness) via photoluminescence of the heavily doped GaAs contact layer indicates comparable intensity between the bulk Ge control and the best performing Ge/Si sample. The two samples also showed comparable photoluminescence intensity in the GaInP base region with a peak shift in the Ge/Si sample which may be attributable to either strain or compositional ordering effects in the GaInP base. Electrical characterization of the bonded Ge/Si interface of structures formed by bonding p<sup>++</sup>-Ge( $10^{19} \text{ cm}^{-3}$ ) with both p<sup>++</sup>-Si( $10^{20} \text{ cm}^{-3}$ ) and n<sup>++</sup>-Si( $10^{19} \text{ cm}^{-3}$ ) and annealing to  $400^\circ\text{C}$  shows an interfacial resistance of  $<0.1 \text{ cm}^2$ . No azimuthal twist angle dependence was observed in either p<sup>++</sup>-Ge/p<sup>++</sup>-Si or p<sup>++</sup>-Ge/n<sup>++</sup>-Si structures indicating no dependence of the interface electrical properties on the twist angle of the bond and the resulting interfacial screw dislocation network. Future work to be reported will include characterization of the minority carrier performance of MOCVD grown GaAs material by time-resolved photoluminescence studies of AlGaAs/GaAs double heterostructures grown on Ge/Si substrates to allow determination of bulk minority carrier lifetime and heterointerface surface recombination velocity. The double heterostructures will be used to optimize the Ge surface preparation for MOCVD growth. Preliminary results on Ge buffer layer smoothing show that growing a 250nm thick Ge layer on a Ge/Si sample at a sample temperature of  $450^\circ\text{C}$  at  $0.1 \text{ nm-s}^{-1}$  reduced the surface roughness from 12nm to 1.5nm while having a finished surface that showed a mesa-type morphology with a top surface roughness of  $<1 \text{ nm}$  offering promise for future improvement of the quality of epitaxial growth on these surfaces.

## 2:20 PM Student

**K4, Long Wavelength InGaAs/InAlAs/InP-GaAs/AlGaAs Avalanche Photodiode Implemented by Direct Wafer Bonding:** *J. B. Hurs<sup>†</sup>; X. G. Zheng<sup>†</sup>; X. Sun<sup>†</sup>; S. Wang<sup>†</sup>; Joe C. Campbell<sup>†</sup>; Archie L. Holmes<sup>†</sup>;* <sup>†</sup>University of Texas at Austin, Electl. & Compu. Eng., 10100 Burnet Rd., Austin, TX 78712 USA

In this talk, we report on the design and implementation of a novel high-performance wafer-bonded avalanche photodiode (APD) for long-wavelength applications consisting of an  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  absorber and AlGaAs multiplication region. The InP and GaAs wafers were grown in a Varian GEN-II MBE chamber using standard group-II sources and a valved As cracker. The bonding procedure begins by etching an array of  $5\text{-}\mu\text{m}$ -wide and  $1\text{-}\mu\text{m}$ -deep channels with a pitch distance of  $500 \mu\text{m}$  in the GaAs wafer surface with  $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$  (1:1:10). These channels have been found to improve the quality of the fused interface by enhancing the transport of desorbed gases from the bonding interface and reducing the defect density in terms of voids and bubbles. Both the InP and GaAs wafers were cleaned to remove contaminants. Details of the cleaning procedure used will be outlined in the talk. For the bonding, the samples were placed in graphite fixtures and pressure was applied before placing them in the bonding furnace. The applied pressure was estimated to be  $1\text{-}2 \times 10^6 \text{ Pa}$  at room temperature. After annealing the InP substrate was removed to the InGaAs etch stop using  $\text{HCl}:\text{H}_2\text{O}$  (3:1). The bonding of  $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  to GaAs was investigated at  $600^\circ\text{C}$ ,  $650^\circ\text{C}$ , and  $700^\circ\text{C}$  under  $\text{N}_2$  and  $\text{H}_2$  atmospheres using a simple p-i-n structure to observe the effect of the bonding conditions on the measured dark current. It was found that there is an optimum temperature,  $650^\circ\text{C}$ , for achieving the lowest dark current in the p-i-n devices. Also, using  $\text{H}_2$  instead of  $\text{N}_2$  decreases the dark current possibly by reducing the amount of dangling bonds at the bonding interface. It should also be noted that despite

having the  $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{GaAs}$  bonding interface in the high electric field region of the p-i-n structure, the dark current under the best bonding conditions is the same level as the MBE grown reference sample up to 10V reverse bias. From this experiment,  $650^\circ\text{C}$  and  $\text{H}_2$  was chosen for bonding of the SACM APD structure consisting of a  $1 \mu\text{m}$  InGaAs absorption and AlGaAs multiplication regions. The current-voltage characteristics of the bonded APD devices and a similar APD device grown on InP with InAlAs multiplication and 1500nm InGaAs absorption regions were measured. These measurements revealed that at breakdown the dark current of both the bonded and unbonded reference sample are approximately the same. At a breakdown voltage of 37V the dark current is approximately 18nA for a  $150 \mu\text{m}$  diameter device. Using the direct wafer bonding technique, we successfully demonstrated an avalanche photodiode in which an InGaAs absorber chosen for long wavelength applications was bonded to an AlGaAs multiplication region.

## 2:40 PM

**K5, Wafer Fusion Enables the First AlGaAs/GaAs/GaN Double Heterojunction Bipolar Transistor (DHBT):** *Sarah Estrada<sup>†</sup>; Andrew Huntington<sup>†</sup>; Andreas Stonas<sup>†</sup>; Huili Xing<sup>†</sup>; Larry Coldren<sup>†</sup>; Steven Denbaars<sup>†</sup>; Umesh Mishra<sup>†</sup>; Evelyn Hu<sup>†</sup>;* <sup>†</sup>University of California, Dept. of Matls. & Electl. & Compu. Eng., Santa Barbara, CA 93106 USA

The large breakdown field and anticipated saturation velocity of GaN make this novel material particularly promising for high-frequency, high-power devices. With this goal in mind, quite a few researchers are working to develop GaN-based heterojunction bipolar transistors (HBTs). Although results have been promising, there are still outstanding materials issues: AlGaN/GaN HBTs appear to be limited by large acceptor ionization energies and low hole mobilities. We are developing an AlGaAs/GaAs/GaN HBT, which can potentially combine the high-breakdown voltage of GaN with the high mobility of the technologically mature AlGaAs/GaAs heterostructure. Because the high degree of lattice mismatch between GaAs (lattice constant of 3.65Å) and GaN (3.19Å) precludes an all-epitaxial formation of this device, we have fabricated the GaAs/GaN heterostructure via wafer fusion. The AlGaAs/GaAs emitter/base was grown by molecular beam epitaxy (MBE) at  $585^\circ\text{C}$  in a Varian Gen-II system. A sacrificial layer ( $0.5 \mu\text{m}$ ) of undoped AlAs was grown on a (100) Si-doped n<sup>+</sup> GaAs substrate, followed by a contact layer ( $0.1 \mu\text{m}$  n-GaAs doped with  $1 \times 10^{19} \text{ Si}$ ), the device emitter ( $0.12 \mu\text{m}$  nAl<sub>0.15</sub>Ga<sub>0.85</sub>As flanked on top and bottom by  $0.03 \mu\text{m}$  Al grading at  $x=0$  to 0.3, all doped with  $5 \times 10^{17} \text{ Si}$ ), and finally the device base ( $0.15 \mu\text{m}$  p-GaAs doped with  $1 \times 10^{19} \text{ C}$ ). Carbon, rather than beryllium, was chosen as the p-type dopant in order to minimize dopant diffusion during the high-temperature fusion procedure. The unintentionally doped GaN collector (nominal  $5 \times 10^{16} \text{ Si}$ ) was grown by metal-organic chemical vapor deposition (MOCVD) on c-plane (0001) sapphire at  $1160^\circ\text{C}$ . Prior to fusion "escape channels" were etched into GaAs, to prevent liquid and gas from being trapped at the interface when GaAs and GaN were later brought together. Wafers were cleaved into squares (5-7mm) and cleaned with acetone and isopropanol. The samples underwent two sequential oxidation (first by oxygen plasma then by UV-ozone) and oxide removal steps (in  $\text{NH}_4\text{OH}$ ). n-GaN and p-GaAs were rinsed in methanol, joined together in methanol, and annealed at  $750^\circ\text{C}$  for 1 hour under a uniaxial pressure of 2 MPa in a nitrogen ambient. After fusion the GaAs substrate was removed via wet spray etching in  $\text{H}_2\text{O}_2:\text{NH}_4\text{OH}$ . HF was used to remove the sacrificial AlAs, revealing the n-GaAs emitter contact layer onto which Au/Ge/Ni was deposited and annealed. Emitter ( $1 \times 10^{-5} \text{ cm}^2$ ) and base mesas ( $5 \times 10^{-5} \text{ cm}^2$ ) were defined via wet etching in  $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ . Unannealed Zn/Au contacts were deposited onto the p-GaAs base. Unalloyed Al/Au contacts were made to the n-GaN collector. Our initial HBT demonstrates a current gain less than one; however the diode characteristics, common-emitter characteristic, and Gummel plot are well-behaved and demonstrate reasonable output conductance ( $\sim 100 \text{ A/cm}^2$ ). We believe that optimization of wafer fusion conditions will produce improved electrical performance.

## 3:00 PM Break

## 3:20 PM

**K6, Heterogeneous Assembly of III-V Devices onto Silicon Using Electro-Fluidic Assembly:** *Christopher Nordquist<sup>†</sup>; Nikolai T. Moshegov<sup>†</sup>; Theresa S. Mayer<sup>†</sup>;* <sup>†</sup>Pennsylvania State University, Dept. of Electl. Eng., 121 EE E., University Park, PA 16802 USA

The heterogeneous integration of III-V high-speed and light-emit-

ting devices with silicon CMOS circuitry will provide increased performance and functionality for communication and signal processing systems. Pseudo-monolithic integration of these devices will result in lower circuit parasitics, reduced system size and weight, and lower power consumption. In this work, we present an electro-fluidic assembly technique for placing and aligning III-V devices onto silicon substrates. InP-based devices, including LEDs and HBTs, are grown and fabricated on InP substrates. Au/Sn/Au bumps are plated over the devices and the wafer is then inverted and fastened to a silicon carrier wafer using black wax. The InP substrate is removed and backside processing is performed, including etching mesas and plating contact bumps. The wax is dissolved to release the devices, which are then rinsed, cleaned, and suspended in isopropanol. To serve as the alignment substrates, heavily doped silicon wafers are thermally oxidized to produce a 2  $\mu\text{m}$  thick dielectric layer. The oxide layer is covered with a Ti/Au plane patterned with apertures that are similar in shape and size to the parts. The wafer is inserted into a fixture that confines the fluid and provides an electrode approximately 2mm above the ground plane which can be used to generate long-range electric fields in the solution in addition to the short-range electric fields that can be generated by biasing the metal plane and substrate. The liquid containing the parts is dispensed into the fixture while the metal plane is grounded and the substrate and upper electrode are biased with a 200 V, 1 kHz sinusoid. The parts are attracted to the apertures by long-range dielectrophoretic forces and aligned into place due to the maximization of energy stored in the capacitor formed between the substrate and the gold bump on top of the device, yielding an average alignment accuracy of approximately 10  $\mu\text{m}$ . After the devices are assembled and aligned into place, they are fastened in place by heating the substrate to melt the Au/Sn solder on the device bump. A planarizing layer of benzocyclobutene (BCB) is spun on the wafer and etched back to expose the plated gold contacts on the devices, followed by electroplated gold interconnects to contact the devices. Using this process, both InP/InGaAs diodes and InP/InGaAs/InP DHBTs have been fabricated and assembled onto silicon wafers. Prior to and after the assembly, the DHBTs demonstrated good electrical properties, including junction ideality factors of about 1.1, current gains of about 40, and common-emitter breakdown voltages over 8 V. These device properties indicate that the release and assembly processes do not damage the devices and are suitable for heterogeneous integration, providing a rapid technique for assembling and fabricating microelectronic circuit.

### 3:40 PM Student

**K7, Monolithic Integration of Lattice-Mismatched Semiconductors with Si via Wafer Bonding:** *Arthur J. Pitera*<sup>1</sup>; Christopher W. Leitz<sup>1</sup>; Minjoo L. Lee<sup>1</sup>; Zhiyuan Cheng<sup>1</sup>; Eugene A. Fitzgerald<sup>1</sup>; <sup>1</sup>Massachusetts Institute of Technology, Dept. of Matls. Sci. & Eng., 77 Massachusetts Ave., Cambridge, MA 02139 USA

The current challenge in monolithic integration of lattice-mismatched semiconductors with Si is fabrication of high-quality device layers on a Si substrate. Growth of Ge or GaAs films directly on Si results in threading dislocation densities as high as  $10^9\text{cm}^{-2}$ , rendering the material useless for minority carrier device applications. While high-quality Ge and GaAs on Si has already been demonstrated using SiGe compositionally graded buffers, more convenient integration of III-V devices with Si requires removal of the thick ( $\sim 10\mu\text{m}$ ) underlying graded layer. One solution is film transfer via wafer bonding and layer exfoliation by ion implantation of hydrogen. Traditional wafer bonding allows transfer of epitaxial films of arbitrary composition and lattice constant to Si. However, the differing coefficients of thermal expansion of Si relative to GaAs and Ge limit the annealing temperature that these bonded pairs can be exposed to. In addition, wafer size mismatch limits their use to non-leading edge fabrication facilities. Using Ge virtual substrates, Ge or GaAs films can be transferred to Si by eliminating the large thermal strain energy that arises when bulk Ge or GaAs substrates are bonded to Si. In this study, the processing issues of transferring films from Ge virtual substrates to Si will be discussed, including wafer curvature, virtual substrate planarization, protection of the Ge surface during chemical processing and thermal budget limitations. Unengineered thermal stress in Ge virtual substrates can cause wafer deflections as large as  $40\mu\text{m}$  across a  $100\text{cm}$  wafer, rendering the virtual substrates impossible to bond. One solution to wafer curvature has been addressed by fabricating the virtual substrate on double-side polished wafers which nearly eliminate all wafer deflection. Our Ge virtual substrates exhibit RMS surface roughness of 8nm on a

$10\times 10\mu\text{m}$  scale which must be removed prior to wafer bonding. Application of a standard Si CMP process to Ge yields a polish rate of  $<0.5 \text{ \AA}/\text{sec}$ . Therefore, alternative techniques were explored to planarize the substrates prior to bonding. A Si planarization layer was deposited on the Ge virtual substrate, enabling CMP of the surface. This layer also serves to protect the Ge from subsequent chemical cleaning steps before wafer bonding to a Si host wafer, resulting in a thin Ge film directly on Si. Experiments utilizing an oxide planarization layer were also carried out to fabricate a Ge/SiO<sub>2</sub>/Si structure. Although the Ge CMP issues can be solved, the Ge/SiO<sub>2</sub>/Si structure is an attractive platform for integrated optics due to high dielectric contrast and excellent device isolation.

### 4:00 PM Student

**K8, Silicon on Diamond Formed by Wafer Bonding:** *Gleb N. Yushin*<sup>1</sup>; Scott D. Wolter<sup>1</sup>; Alexander V. Kvit<sup>1</sup>; Brian R. Stoner<sup>2</sup>; John T. Prater<sup>3</sup>; Zlatko Sitar<sup>1</sup>; <sup>1</sup>North Carolina State University, Matls. Sci. & Eng., 1001 Capability Dr., RB-I, Rm. 215, Raleigh, NC 27695 USA; <sup>2</sup>MCNC, Matl. & Elect. Techs. Div., RTP, Raleigh, NC 27709 USA; <sup>3</sup>Army Research Office, Matls. Sci. Div., RTP, Raleigh, NC 27709 USA

The conventional SOI technology employs silicon dioxide as the buried insulator layer and is limited to low power devices due to difficulties in thermal management. Diamond as a buried insulator has the potential for solving this problem due to its high thermal conductivity ( $\sim 20 \text{ Wcm}^{-1}\text{K}^{-1}$ ; a value 1000 times higher than that of silicon dioxide) and high breakdown voltage. In this work, silicon-on-diamond structures have been produced by wafer bonding. For this purpose, diamond films grown on (100) silicon were polished to an RMS roughness of 15nm and directly bonded to the silicon in a dedicated ultrahigh vacuum bonding chamber. Successful bonding was observed at temperatures as low as 950°C under a uniaxial mechanical stress of 32 MPa. Scanning acoustic microscopy indicated macroscopically complete bonding at fusion temperatures above 1150°C, and some cracking of the diamond film. Cross-section transmission electron microscopy (XTEM) of the same specimens revealed that the bonded Si wafer retained its high crystalline quality and no discernable defects in the fused silicon were observed within the sampling region. An amorphous, 30nm thick interfacial layer consisting of silicon, carbon and oxygen formed between the diamond and silicon. In addition, the interface showed some microscopic voids, probably connected to the roughness of diamond surface. To enhance the bonding process, an amorphous Si layer was deposited on diamond and polished to an RMS roughness of 1nm. Bonding to silicon wafers was performed at 400°C and followed by short time annealing at high temperature. The process resulted in the formation of a strong bond over the whole area of the specimen and recrystallization of the amorphous Si interlayer. Detailed process parameters and results of different analyses, including XTEM will be presented.

### 4:20 PM Student

**K9, A Metallic Bonding Method for the Fabrication of Long-Wavelength VCSELs:** *Hung C. Lin*<sup>1</sup>; Wei H. Wang<sup>2</sup>; Kuo L. Chang<sup>1</sup>; Gregory W. Pickrell<sup>1</sup>; Kuang C. Hsieh<sup>1</sup>; Keh Y. Cheng<sup>1</sup>; <sup>1</sup>University of Illinois at Urbana-Champaign, Electl. & Compu. Eng., 208 N. Wright St, Urbana, IL 61801 USA; <sup>2</sup>Chunghwa Telecom Company, Ltd., Telecom. Labs., 12, Ln. 12, Sec. 5, Mintzu Rd., Taoyuan, Taiwan 320

A novel metallic bonding method using AuGeNiCr as the bonding medium was developed for the fabrication of long-wavelength vertical-cavity surface-emitting lasers (VCSELs). The metallic bonding process started with cleaning the samples in ultrasonic baths of acetone, methanol, isopropyl alcohol and deionized water in sequence. Then, the bonding metals were evaporated on two cleaned samples to be bonded together. The two samples were then brought to a close contact with the bonding metals facing each other. Samples were transferred to an open tube quartz furnace set at 320°C in a nitrogen ambient for one hour to complete the bonding process. Cross-sectional transmission electron microscopy shows that the bonding interface is smooth, uniform and damage-free. The feasibility of the metallic bonding process for VCSEL fabrication was further investigated by evaluating the thermal stability and optical quality of a bonded VCSEL structure. A 6.5 period Al-oxide/Si distributed Bragg reflector (DBR) deposited on a bulk InP wafer was bonded to a Si substrate by this metallic bonding process. Then, the InP substrate was completely removed by HCl chemical etching and left only the Al-oxide/Si DBR on the Si substrate. The reflectivity spectra of the DBR measured as deposited and after bonding were compared. The stop-band distribution of the DBR measured after bonding is consistent with

the spectrum measured as deposited. The reflectivity of the DBR after bonding is above 99% at wavelengths around 1.55  $\mu\text{m}$ , which is of the same level as that measured from the as-deposited DBR. Thus, the bonding metals as well as the bonding process does not degrade the reflectivity of the DBR. Using the same technique, a 2 $\mu\text{m}$  GaInAsP/InP VCSEL cavity sandwiched by two Al/Si-oxide DBRs designed for a wavelength of 1.55  $\mu\text{m}$  was bonded to a Si substrate. During the fabrication process, the sample was annealed to 420°C for 5 min in a hydrogen ambient. As inspected by Nomarski microscopy and scanning electron microscopy, no degradation was found on the bonded films after the annealing process and the bonding interface remains smooth and uniform after the thermal cycle. The reflectivity spectrum measured from the bonded VCSEL cavity shows a clear resonance at  $\sim 1.55 \mu\text{m}$ . In conclusion, the low temperature (320°C) multi-layered metallic bonding method can integrate various materials for VCSEL fabrication. The bonded VCSEL structure demonstrated good thermal stability and optical quality. In addition, the metallic bonding is less stringent on process latitude as it does not require any special treatment to the bonding surfaces. Thus, this novel bonding method employing multi-layered metals as the bonding medium has a great potential in the fabrication of VCSELs. The device results of 1.55  $\mu\text{m}$  GaInAsP/InP VCSELs fabricated by this bonding process will be presented.

#### 4:40 PM

**K10, Improvements in Wafer-Bonded AlGaInP Light-Emitting Diodes by Various Mirror Substrates:** Ray H. Horng<sup>1</sup>; Chih R. Chung<sup>2</sup>; Shao H. Huang<sup>1</sup>; Chi Y. Chiu<sup>1</sup>; Dong S. Wu<sup>3</sup>; <sup>1</sup>National Chung Hsing University, Inst. of Precision Eng., 250, Kuo Kuang Rd., Taichung 402 Taiwan; <sup>2</sup>Da-Yeh University, Inst. of Electl. Eng., 112, Shan-Jeau Rd., Chang-Hwa 515 Taiwan; <sup>3</sup>National Chung Hsing University, Dept. of Matls. Eng., 250, Kuo Kuang Rd., Taichung 402 Taiwan

High-efficiency light-emitting diodes (LEDs) operating in the wavelength region from red to green light have been recently realized employing the AlGaInP alloy system grown on a lattice-matched GaAs substrate. However, the efficiency of these devices is limited by the absorbing GaAs substrate. This problem can be overcome by wafer-bonding the AlGaInP LEDs with a transparent substrate or with a mirror substrate (MS). For the MS-LED structure, the metallic interlayer can not only be used as an adhesive, but also a reflective mirror. In our previous study, the AlGaInP LED with a Au/AuBe/SiO<sub>2</sub>/Si MS (structure A) has been demonstrated with superior performance than the conventional AlGaInP LED with an absorbing GaAs substrate. However, the adhesion properties of the MS LEDs can not afford the backend process including chip dicing and wire bonding. It is found that the insertion of the Pt/Ti interlayer (structure B) can increase the adhesion behavior. Thus it can ensure the complete MS LED structure after the backend process. Furthermore, the reflectivity of the structure B is higher than the structure A. Over 90% in reflectivity of the MS with structure B can be achieved as the incident wavelength varied from 600 to 900nm. However, Be in the AuBe ally will react with the Pt film and produces the crystallographic product of Be<sub>3</sub>Pt during the bonding temperature. It yields a degraded optical reflectivity of the mirror substrate. Thus AuZn is proposed to replace AuBe in the mirror film stacks (structure C). The individual thickness effects of the Au/AuZn/Au multilayers in structure C were investigated. It is found that the luminance intensity of AlGaInP LED with the Au (40 nm)/AuZn/Au in the structure C can reach a maximum of  $\sim 200$  mcd at operation current 20 mA and then decreases as the Au thickness increases to 60nm. The thicker Au layer will deteriorate the ohmic contact to p-AlGaInP and raises the forward operating voltage. Finally, a comparison of the luminance intensities of the AlGaInP LEDs with the structures B and C was made. The performance of the AlGaInP LED with structure C (Au/AuZn/Au/Pt/Ti/SiO<sub>2</sub>/Si) is confirmed to be better than other mirrors. Details of the material issues and mechanisms of the wafer-bonded AlGaInP LEDs with various mirror film stacks will be discussed in this paper.

## Session L: Nitrides: Transport and Devices

Wednesday PM Room: UCEN Lobero  
June 26, 2002 Location: University of California

*Session Chairs:* Jim Speck, University of California–Santa Barbara, Matls. Dept., Santa Barbara, CA 93106 USA; M. Asif Khan, University of South Carolina, ECE Dept., Photonics & Microelect. Lab., Columbia, SC 29208 USA

#### 1:20 PM

**L1, Comparative Study of AlGaIn/GaN HEMTs Grown by MBE on Semi-Insulating HVPE GaN Templates and Directly on Sapphire:** M. J. Manfra<sup>1</sup>; N. Weimann<sup>1</sup>; J. W.P. Hsu<sup>1</sup>; L. N. Pfeiffer<sup>1</sup>; K. W. West<sup>1</sup>; D. V. Lang<sup>2</sup>; R. J. Molnar<sup>3</sup>; <sup>1</sup>Lucent Technologies, Bell Labs., Semiconductor Physics Rsrch., 600 Mountain Ave., Murray Hill, NJ 07974 USA; <sup>2</sup>Agere Systems, Elect. Matls., 600 Mountain Ave., Murray Hill, NJ 07974 USA; <sup>3</sup>Massachusetts Institute of Technology, Lincoln Lab., Electrooptical Matls., 244 Wood St., Lexington, MA 02420 USA

Our recent work has shown thick ( $\sim 15$ (Structure A)m) GaN templates grown by hydride vapor-phase epitaxy (HVPE) to be a useful substrate for molecular beam epitaxy (MBE) overgrowth studies of GaN and its alloys. The combination of low threading dislocation density and smooth surfaces present in HVPE GaN templates has proven invaluable for fundamental studies of MBE growth and electron transport. The record low temperature two-dimensional electron gas (2<sup>o</sup>) mobility now stands at 75,000cm<sup>2</sup>/Vs for AlGaIn/GaN heterostructure grown by plasma-assisted MBE on a HVPE template with a low threading dislocation density of  $\sim 2 \times 10^8 \text{cm}^{-2}$ . Our present investigations are focused on the use of zinc-doped semi-insulating HVPE GaN as a substrate for the growth and fabrication of high electron mobility transistors. To date, there exists surprisingly little data detailing the use of GaN templates for the MBE growth and fabrication of high electron mobility transistors (HEMTs) operating at room temperature. Proper transistor operation requires that the 2<sup>o</sup> be electrically isolated from the substrate and that the substrate to be semi-insulating. We detail the development of semi-insulating HVPE GaN that has been intentionally compensated with Zn to produce resistivities of  $\sim 10^8 \Omega \text{cm}$ . Proper control of MBE growth conditions allows for the production of Al<sub>0.25</sub>Ga<sub>0.75</sub>N/GaN heterostructures that routinely display room temperature mobilities of 1500cm<sup>2</sup>/Vs at a density of  $1.0 \times 10^{13} \text{cm}^{-2}$ . Capacitance-voltage profiling is used to locate possible sources of parallel conduction. The sheet charge of these structures displays little temperature dependence from 300 to 4K and fabricated transistors show good pinch-off behavior. In order to explore the possible advantages of semi-insulating HVPE GaN, we have also investigated the direct MBE growth of AlGaIn/GaN heterostructures on sapphire substrates. As we will show, vastly different nucleation and MBE growth conditions must be employed to achieve high quality HEMTs via direct growth via MBE on sapphire. The change in MBE growth conditions from those used with HVPE templates highlights the importance of defect density reduction during the early stages of MBE growth directly on sapphire. Using a two-stage growth process HEMT structures grown on sapphire display room temperature mobilities of  $\sim 1200 \text{cm}^2/\text{Vs}$  at sheet density  $1.0 \times 10^{13} \text{cm}^{-2}$ . Comparison between devices fabricated on HVPE GaN and sapphire substrates allows us to isolate device performance characteristics unique to each substrate.

#### 1:40 PM Student

**L2, High Performance AlGaIn/GaN HEMTs on Semi-Insulating SiC Substrates Grown by Metalorganic Chemical Vapor Deposition:** Michael M. Wong<sup>1</sup>; Uttiya Chowdhury<sup>1</sup>; David T. Becher<sup>2</sup>; Delphine Sicault<sup>1</sup>; Jonathan C. Denyszyn<sup>1</sup>; Ting Gang Zhu<sup>1</sup>; Jin Ho Choi<sup>1</sup>; Milton Feng<sup>2</sup>; Russell D. Dupuis<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Electl. & Compu. Eng., Microelect. Rsrch. Ctr., Austin, TX 78712-1100 USA; <sup>2</sup>University of Illinois at Urbana–Champaign, Electl. & Compu. Eng., Ctr. for Compound Semiconductor Microelect., Urbana, IL 61801 USA

A high current gain cut-off frequency along with a high saturation current is of essential importance for high-frequency and high-power

device applications such as AlGaIn/GaN microwave-power HEMTs. Conventional modulation-doped AlGaIn/GaN HFET structures have been extensively studied. However, other HFET device elements, such as delta-doping and binary barriers, can potentially improve the high-power transistor electrical characteristics. In this study, we present the results of a series of devices utilizing various novel epitaxial device structures. We demonstrate devices that exhibit high mobility-sheet charge products, large maximum drain currents, high frequency response, and large transconductance values. The AlGaIn/GaN heterostructures of this work were grown by low-pressure metalorganic chemical vapor deposition on 2.0 in. diameter 6H *n*-type and 4H semi-insulating SiC, and sapphire substrates. From DC device comparisons, there is a clear advantage in using SiC substrates. The use of a thin AlN barrier layer at the AlGaIn-GaN interface can increase the effective conduction band offset to increase the sheet charge density without reducing the mobility, and reduce alloy scattering, resulting in a large  $n_s\mu$  product. In addition, delta doping can be used to further increase the charge density in the 2<sup>o</sup>. An AlGaIn/AlN/GaN structure utilizing both these features resulted in 300K Hall mobility of 1,058 cm<sup>2</sup>/V-s and a sheet carrier density of  $2.35 \times 10^{13}$  cm<sup>-2</sup>, yielding a large  $n_s\mu$  product of  $\sim 2.5 \times 10^{16}$ /V-s. This structure should be capable of high-speed operation at high power densities. We have achieved peak DC transconductances  $g_m \sim 240$  mS/mm with maximum current densities  $I_{DSmax} \sim 1.3$ -1.5 A/mm at  $V_G = +1$  V. Devices from several wafers have shown this performance. High-frequency measurements yielded an extrapolated (20 dB/decade)  $f_t = 50$  GHz and  $f_{max} = 130$  GHz. We will report on the high-power performance of these devices.

## 2:00 PM Student

**L3, AlGaIn/GaN HEMTs on Fe Doped Semi-Insulating GaN: Material and Device Characteristics:** *Sten Heikman*<sup>1</sup>; *Stacia Keller*<sup>1</sup>; *Naiqian Zhang*<sup>1</sup>; *Likun Shen*<sup>1</sup>; *Robert Coffie*<sup>1</sup>; *Dario Buttari*<sup>1</sup>; *Steven P. Denbaars*<sup>2</sup>; *Umesh K. Mishra*<sup>1</sup>; <sup>1</sup>University of California-Santa Barbara, Electl. & Compu. Eng. Dept., Santa Barbara, CA 93106-956 USA; <sup>2</sup>University of California-Santa Barbara, Matls. Dept., Santa Barbara, CA 93106 USA

We have grown high electron mobility transistor (HEMT) structures by MOCVD on a newly developed semi-insulating GaN on sapphire base-layer, showing excellent DC and RF performance. The new growth process for semi-insulating GaN employs Fe deep acceptors to compensate the residual donors, using Ferrocene as precursor. The technique is robust with respect to variations in growth conditions, for instance growth temperature. Two different base-layer structures were grown, labeled A and B. Base-layer A was Fe doped only during the first 0.3  $\mu$ m, and the top 2.3  $\mu$ m was nominally undoped. Base-layer B was Fe doped during the first 0.65  $\mu$ m, followed by a 50nm AlN layer, and finally a 1.9  $\mu$ m undoped GaN layer. With a Fe concentration of  $\sim 3 \times 10^{18}$  cm<sup>-3</sup>, base-layer A had a sheet resistance of 7E9 ohm/sq, and base-layer B had a sheet resistance of 3E9 ohm/sq. X-ray diffraction rocking curves indicated superior structural quality for base-layer A, with a full-width at half-maximum of 253 arcsec for the (002) reflection and 481 arcsec for the (102) reflection, compared to base-layer B, which had a FWHM of 281 arcsec for the (002) reflection and 676 arcsec for the (102) reflection. On top of the semi-insulating base-layers a standard HEMT structure was grown: 0.5nm AlN layer followed by 30nm AlGaIn (Al composition 34%). Hall measurements showed similar characteristics for both base-layers, with charges of  $1.5 \times 10^{13}$  cm<sup>-2</sup> and mobilities around 1500-1600 cm<sup>2</sup>/Vs. Devices with 0.7  $\mu$ m gate length were fabricated from HEMT structures on both types of base-layers. The devices on base-layer A generally had a low maximum current, around 400 mA/mm, despite good Hall data. We believe this is related to the high concentration of deep traps in the base-layer. In contrast, the devices on base-layer B showed high maximum currents, around 1 A/mm. Base-layer B was designed with the intention of isolating the deep traps (the Fe doped layer) from the active region of the device, through the insertion of a 50nm AlN layer above the Fe doped layer. Close agreement between DC and 80 is pulsed gate IV-curves was observed for these devices, indicating much reduced charge trapping. After SiN passivation of the devices the RF power performance was measured at 8.2 GHz. At a drain bias of 23 V a maximum output power of 4.2 W/mm, and a maximum power added efficiency of 39%, were measured. These results are among the best reported for AlGaIn/GaN HEMTs on sapphire.

## 2:20 PM

**L4, Layer Structure Optimization for AlGaIn/GaN HFET Applications:** *Delphine Sicault*<sup>1</sup>; *Michael M. Wong*<sup>1</sup>; *Uttiya Chowdhury*<sup>1</sup>; *David*

*T. Becher*<sup>2</sup>; *Ting Gang Zhu*<sup>1</sup>; *Jonathan C. Denyszyn*<sup>1</sup>; *Jin Ho Choi*<sup>1</sup>; *Milton Feng*<sup>2</sup>; *Russell D. Dupuis*<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Electl. & Compu. Eng., PRC/MER-R9900, Austin, TX 78712-1100 USA; <sup>2</sup>University of Illinois at Urbana-Champaign, Electl. & Compu. Eng., 208 N. Wright St., Urbana, IL 61801 USA

AlGaIn/GaN heterojunction field-effect transistors (HFETs) are very attractive for high-power and high-temperature microwave applications because of superior electronic transport properties. In particular, a large conduction-band discontinuity and inherent polarization effects of Group III-nitrides induce a two-dimensional electron gas (2<sup>o</sup>) at the AlGaIn/GaN interface, allowing a large drain current which is necessary for high output power. Therefore, increasing the mobility and the density of this 2<sup>o</sup> is of essential importance for power HFETs. In this study, we have compared different designs of heterostructures in order to compare their influence on the transport properties and DC performance of AlGaIn/GaN HFETs. Furthermore, HFET growth conditions can be optimized using this rapid feedback approach. The AlGaIn/GaN heterostructures presented in this work have been grown by low-pressure metalorganic chemical vapor deposition on 2.0 inch diameter *n*-type 6H SiC and 4H SiC substrates. We have investigated four different epitaxial structures to compare the corresponding HFET device performance. The first is a standard HFET structure with a simple undoped AlGaIn/GaN heterojunction. In the second structure, an AlN barrier is inserted between the AlGaIn and GaN layers. This structure is aimed at improving the 2<sup>o</sup> mobility, by increasing the effective conduction-band discontinuity and reducing the alloy disorder scattering. The two last structures were modulation-doped and delta-doped HFETs, which included an AlN barrier. These structures were first characterized using a quick HFET device processing procedure. Unlike conventional HFETs with an open-finger gate geometry, the gate of a quick-process HFET forms a closed ring. The drain contact is put inside the ring, whereas the source contact surrounds the gate. This structure requires a considerably simplified processing procedure, since it does not require mesa etching or the formation of contact pads. This process allows a quick feedback to epitaxial growth, while providing an accurate evaluation of the device performance of the material. We demonstrate the influence of the AlN barrier and the delta-doped or modulation-doped structures in maximizing the  $n_s\mu$  product at 300K. Moreover, the different advantages of each structure can be seen from the  $I_{DSmax} \cdot V_{DS}$  and transconductance values of the 2- $\mu$ m gate length "quick-process" devices. The modulation and delta-doped structures achieve very good maximum drain current density and transconductance values ( $I_{DSmax} = 1,028$  mA/mm,  $g_m = 202$  mS/mm for the modulation-doped structure and  $I_{DSmax} = 1,173$  mA/mm,  $g_m = 139$  mS/mm for the delta-doped one). HFETs with a 0.25- $\mu$ m T-gate were also fabricated from these wafers. We find a good correlation between devices fabricated using both processes, and report very large maximum drain current densities and transconductances for  $L_g = 0.25 \mu$ m:  $I_{DSmax} = 1.35$  A/mm,  $g_m = 208$  mS/mm for the modulation-doped structure and  $I_{DSmax} = 1.18$  A/mm,  $g_m = 137$  mS/mm for the delta-doped HFETs. We will discuss these comparison data in detail.

## 2:40 PM Student

**L5, Investigation of Traps in Doped and Undoped AlGaIn/GaN HEMTs:** *Mike Wolter*<sup>1</sup>; *Peter Javorka*<sup>1</sup>; *Michel Marso*<sup>1</sup>; *Alfred Fox*<sup>1</sup>; *Reinhard Carius*<sup>2</sup>; *A. Alam*<sup>3</sup>; *M. Heuken*<sup>3</sup>; *Hans Lüth*<sup>1</sup>; *Peter Kordos*<sup>1</sup>; <sup>1</sup>Forschungszentrum Juelich, ISG-1, Leo-Brandt-Strasse, Juelich 52425 Germany; <sup>2</sup>Forschungszentrum Juelich, IPV, Leo-Brandt-Strasse, Juelich 52425 Germany; <sup>3</sup>AIXTRON, Kackertstrasse, Aachen 52072 Germany

The performance of high electron mobility transistors (HEMTs) on AlGaIn/GaN heterostructures is limited by a non-negligible concentration of material defects. Unfortunately the trapping of charge at defects, after the application of a high drain-source current, is responsible for current collapse. In order to study the role and the properties of traps in the AlGaIn/GaN layer structures, we investigated the behaviour of doped and undoped HEMTs by photoionization spectroscopy. All the layer structures were grown on sapphire substrates by MOVPE in different reactors. The doped structures consisted of a GaN buffer followed by a undoped AlGaIn spacer, a Si-doped AlGaIn carrier-supply and an undoped AlGaIn barrier layer (Al-content of 18%). The structures differ only in the thickness of the barrier layer and carrier-supply layer, as well as the doping concentration. The undoped structures consisted of a GaN buffer followed by an AlGaIn barrier with the Al-content varying from 20 to 26%. From the Hall data follows that the sheet resistance is nearly iden-



tical (0.9-1  $\dot{U}/\text{sq.}$ ) in all structures investigated. However, measurements on the HEMTs prepared showed significantly different results of their static output characteristics. The spectral dependence of the fractional increase of the collapsed drain current in the linear region and under zero gate bias of the HEMT was measured and then the photoionization cross section was determined. Qualitatively can be seen that the spectral functions have similar shapes and they can be fitted assuming the Lorentz-formula. However, much better fit is obtained by considering additionally the Gaussian broadening of the levels. We could determine two distinct defect levels of about 2.9eV and 3.26eV with a full width at half maximum of about 200meV and 50meV, respectively, in doped structures. A good correlation between the DC performance of the HEMTs and their photoionization cross section was found. It indicates that the same traps are contributing to the current collapse process. Additionally, we found a correlation between the photoionization cross section and the channel-surface distance of HEMTs investigated. From this we assume that certain traps being involved in the current collapse are related to the AlGaIn surface.

### 3:00 PM Break

#### 3:20 PM

**L6, High DC and RF Performances of High Al-Content AlGaIn/GaN HEMTs with 0.25 $\mu\text{m}$  Gate:** *Mi-Ran Park*<sup>1</sup>; Kyu-Seok Lee<sup>1</sup>; Sung-Bum Bae<sup>1</sup>; Doo-Hyeon Yoon<sup>1</sup>; Gil-Ho Kim<sup>1</sup>; Jung-Hee Lee<sup>2</sup>; Vipin Kumar<sup>3</sup>; Ilesanmi Adesida<sup>3</sup>; <sup>1</sup>Electronics and Telecommunications Research Institute, Opto-Elect. Matls. Team, 161 Gajeong-Dong, Daejeon 305-350 S. Korea; <sup>2</sup>Kyungpook National University, The Sch. of Elect. & Electl. Eng., 1370 Sankyuk-Dong, Daegu 702-701 S. Korea; <sup>3</sup>University of Illinois at Urbana-Champaign, Dept. of Electl. & Compu. Eng., 127 Microelectronics Lab., Urbana, IL 61801 USA

AlGaIn/GaN high electron mobility transistors (HEMTs) have great advantages in the field of high frequency and high power applications because of their high currents and high breakdown voltages. We fabricated 0.25  $\mu\text{m}$  gate length and 100  $\mu\text{m}$  gate width AlGaIn/GaN HEMTs with high Al content of 40% grown by metal organic vapor deposition (MOCVD) on sapphire substrates. The epitaxial layers showed the sheet carrier concentration in the range of  $1.27 \times 10^{13} \sim 1.5 \times 10^{13}/\text{cm}^2$  and the electron mobility in the range of  $750 \sim 1090 \text{ cm}^2/\text{Vs}$ . The material structure of the epitaxial layers with and without an undoped GaN cap layer related to the DC and RF performance of the fabricated HEMTs was investigated in this work. In addition to the DC and RF characteristics, we also studied the performance of the gate to drain breakdown voltage and the output power of those devices. The device fabricated on the material without a cap layer exhibited a higher maximum drain current density of 1.16 A/mm at  $V_{\text{ds}}=6.0\text{V}$  and  $V_{\text{g}}=2\text{V}$  and a maximum extrinsic transconductance of 205 mS/mm at  $V_{\text{ds}}=8\text{V}$  and  $V_{\text{g}}=-4.6\text{V}$  compared to 732 mA/mm at  $V_{\text{ds}}=7.5\text{V}$  and  $V_{\text{g}}=2\text{V}$  and 171 mS/mm at  $V_{\text{ds}}=8\text{V}$  and  $V_{\text{g}}=-1.68\text{V}$  for the device with a cap layer. A similar behavior in RF characteristics was also shown for those two different devices. The highest values of unity gain cut-off frequency ( $f_{\text{T}}$ ) and maximum frequency of oscillation ( $f_{\text{max}}$ ) were 58.6 GHz and 115 GHz for the device without a cap layer, respectively. Contrary to those DC and RF characteristics, the experimental results showed higher gate-drain breakdown voltage ( $BV_{\text{gd}}$ ) of -85V for the device fabricated on the epitaxial material with a cap layer than the one without a cap layer. The devices showed the excellent pinch off characteristics and high DC and RF performances.

#### 3:40 PM Student

**L7, Elimination of Current Collapse of AlGaIn/GaN HEMTs with MgO, and  $\text{Sc}_2\text{O}_3$ :** *Ben Luo*<sup>1</sup>; B. P. Gila<sup>2</sup>; J. W. Johnson<sup>1</sup>; A. Onstine<sup>2</sup>; C. R. Abernathy<sup>2</sup>; F. Ren<sup>1</sup>; S. J. Pearton<sup>2</sup>; A. G. Baca<sup>3</sup>; R. J. Shul<sup>3</sup>; A. M. Dabiran<sup>4</sup>; A. M. Wofchack<sup>4</sup>; P. P. Chow<sup>4</sup>; <sup>1</sup>University of Florida, Dept. of Cheml. Eng., Gainesville, FL 32611 USA; <sup>2</sup>University of Florida, Dept. of Matls. Sci. & Eng., Gainesville, FL 32611 USA; <sup>3</sup>Sandia National Laboratories, Albuquerque, NM 87185 USA; <sup>4</sup>SVT Associates, Eden Prairie, MN 55344 USA

AlGaIn/GaN high electron mobility transistors (HEMTs) demonstrate the excellent potential for high power and high efficiency microwave power amplifiers for military and wireless communication applications. With high current drive capacity, the unexpected low power output from microwave operation was addressed as one of the frequent reported problems in GaN-based HEMTs. This significant current collapse was found to be related to surface states which severely induce a reduction in output power and power-added efficiency under large-signal operation.

An effective passivation layer is urgent needed to passivate these surface states in order to prevent further performance degradation. MBE-grown MgO or  $\text{Sc}_2\text{O}_3$  were deposited on  $1.2 \times 100 \mu\text{m}^2$  AlGaIn/GaN with different pre-deposition treatments to find out optimum passivation layer.  $\text{SiN}_x$  layer was deposited in Plasma Therm PECVD chamber at  $255^\circ\text{C}$  with  $\text{SiH}_4$  and  $\text{NH}_3$  as precursors. Oxygen was supplied from an Electron Cyclotron Resonance (ECR) source operating at 2.45GHz, 200W forward power and  $10^{-4}$  Torr pressure. Effusion cells operating at  $\sim 1150^\circ\text{C}$  for Sc and  $380^\circ\text{C}$  for Mg provided the metal flux. The dielectric thickness was  $\sim 100\text{\AA}$  in all cases and several different variations of pretreatments were applied prior to the dielectric deposition. Figure 1 shows the current-voltage characteristic ( $I_{\text{DS}}-V_{\text{DS}}$ ) was taken from  $1.2 \times 100 \mu\text{m}^2$  HEMT before and after MgO deposition with a treatment of 25 mins UV-ozone, then heated to  $300^\circ\text{C}$  for 5 mins prior to cooling to  $100^\circ\text{C}$  for the MgO deposition. After MgO deposition, the HEMTs showed an increased in drain-source current, threshold voltage and extrinsic transconductance, which is consistent with passivation of surface states. Gate pulse measurement was also performed before and after depositing MgO passivation layer. Figure 2 shows the corresponding gate-lag measurements. The large differences between dc and pulsed drain currents of the in-passivated sample, which is consistent with the presence of surface traps that deplete the channel in the access regions between the gate and drain contacts. For the MgO passivated sample, a marked improvement in drain current was observed. This is clear evidence for the assumption that surface states are the cause of the gate-lag phenomena and also that MgO passivation mitigates this problem.  $\text{Sc}_2\text{O}_3$  was also used for passivating the HEMTs and similar results were obtained.

#### 4:00 PM Student

**L8, High Detectivity Solar-Blind AlGaIn Photodetectors Grown by Metalorganic Chemical Vapor Deposition:** *Uttiya Chowdhury*<sup>1</sup>; Charles J. Collins<sup>1</sup>; Michael M. Wong<sup>1</sup>; Tinggang Zhu<sup>1</sup>; Jonathan C. Denyszyn<sup>1</sup>; Jin-Ho Choi<sup>1</sup>; Joe C. Campbell<sup>1</sup>; Russell D. Dupuis<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Electl. & Compu. Eng., Microelect. Rsrch. Ctr., Austin, TX 78712-1100 USA

Photodetectors insensitive to light of wavelengths longer than  $\sim 290\text{nm}$  are known as solar-blind detectors because, due to absorption in the ozone layer, the solar spectrum near the Earth's surface has a sharp drop in intensity for wavelengths shorter than  $\sim 290\text{nm}$ . If operating near the earth's surface, these photodetectors do not see photons from the sun and therefore do not suffer from the presence of a large background noise from solar radiation. Solar-blind photodetectors (SBDs) have many important commercial and defense applications including missile plume detection, biological and chemical agent detection, short range covert communication, etc. In addition, due to convenience of flip-chip mounting to electronic circuitry, many of the applications favor a back-illuminated configuration for these devices. Also, it is desired to drive these devices with the same low voltage bias used in the electronic circuitry for reduced noise and increased detectivity. Therefore, for many SBD applications,  $p-i-n$  diodes made of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  with  $x > 0.4$  are the devices of choice. Fabrication of these devices with a high detectivity has proven to be challenging due to difficulty in obtaining high-quality materials and high doping concentrations. In this work, we describe the growth and fabrication of high-detectivity SBDs and discuss important material growth and device structure issues involved in the realization of high-performance detectors. Back-illuminated SBD  $p-i-n$  structures are typically grown with the  $n$ -side towards the transparent sapphire substrate. If the  $n$ -layer is not transparent to photons of the wavelengths of interest, significant absorption occurs and the external quantum efficiency (EQE) suffers even though the  $p-i-n$  active region may have a high internal quantum efficiency (IQE). However, a transparent  $n$ -type window layer made of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  with  $x > 0.6$  with high  $n$ -type doping has been difficult to achieve due to material quality and electrical conductivity issues. We report the development of high  $n$ -type doping in  $\text{Al}_{0.6}\text{Ga}_{0.4}\text{N}$  and utilization of this material in  $p-i-n$  SBD devices. The resulting photodiodes have a high zero-bias EQE of 53% (responsivity of 0.12 A/W) at 276nm. The EQE has a slight bias-voltage dependence increasing to 58% at a reverse bias of -5 V. The fabricated devices also showed a very low dark current density of  $8.5 \times 10^{-11} \text{ A/cm}^2$  at -5 V reverse bias and a high zero-bias detectivity ( $D^*$ ) of  $3.22 \times 10^{14} \text{ cmHz}^{1/2}\text{W}^{-1}$ . The devices have a sharp solar-blind wavelength selectivity. To our knowledge, these are the highest detectivity and EQE reported for any solar-blind photodiode to date. We will describe the growth, processing, and testing of these device structures.



#### 4:20 PM Student

**L9, AlGaIn/Sapphire Epilayers for Acoustic Wave Devices:** *Tomás Palacios<sup>1</sup>; Fernando Calle<sup>1</sup>; Eva Monroy<sup>1</sup>; Jesús Grajal<sup>2</sup>; Martin Eickhoff<sup>3</sup>; Oliver Ambacher<sup>3</sup>; Rafael Jiménez<sup>4</sup>; Carlos Prieto<sup>4</sup>;* <sup>1</sup>Universidad Politécnica de Madrid, ISOM & Dpto. Ingeniería Electrónica, ETSI de Telecomunicación, Madrid, E-28040 Spain; <sup>2</sup>Universidad Politécnica de Madrid, ETSI de Telecomunicación, Madrid, E-28040 Spain; <sup>3</sup>Technische Universität München, Walter Schottky Institut, Am Coulombwall, Munich, D-85748 Germany; <sup>4</sup>Consejo Superior de Investigaciones Científicas, Instituto de Ciencia de Materiales de Madrid, Madrid, E-28049 Spain

Passive electronic devices based on surface or bulk acoustic waves (SAW and BAW, respectively) have become a key component in many radio-frequency systems. The compactness and reliability of these devices represent an important advantage over the traditional choices like RC discrete circuits and microstrip lines in the 50 MHz-1 GHz frequency range. However, in order to extend its applicability over 1 GHz, further research is needed both on new materials with high coupling constant and surface sound velocity, and on submicron technology to reduce the critical dimensions of the device. III-Nitrides represent one of the most promising candidates for high frequency applications. In this work, different acoustic-wave-related characteristics of AlGaIn will be discussed and devices operating above 1 GHz will be demonstrated. AlGaIn epilayers (1 to 2  $\mu\text{m}$  thick) were grown on c-plane sapphire substrates by plasma enhanced molecular beam epitaxy. The high structural quality of the samples was confirmed by atomic force microscopy and X-ray diffraction. The acoustic wave propagation in AlGaIn samples was studied by Brillouin spectroscopy, finding good agreement with simulations. Both bulk and surface acoustic velocities were measured, obtaining values of  $\sim 11200$  m/s and  $\sim 5500$  m/s respectively in AlN. SAW pass-band filters have been fabricated on different  $\text{Al}_{1-x}\text{Ga}_x\text{N}$  ( $0 \leq x \leq 1$ ) samples to analyze several acoustic-related properties of nitrides. Finger width and pitch range from 0.5 to 6  $\mu\text{m}$ . A two-step e-beam lithographic procedure and a novel resist/metal scheme were used to define the submicronic patterns. Center frequencies above 1.2 GHz were obtained on AlN and a SAW velocity around 5000 m/s was measured. These values fit well with simulations. The influence of the substrate on the SAW velocity becomes obvious when increasing the finger-to-finger period. The effect of the substrate was also important when studying the variation of the center frequency of the filters with temperature. The RF characteristics of a 217 MHz SAW filter were evaluated in the temperature range from  $-220^\circ\text{C}$  to  $130^\circ\text{C}$ . A thermal coefficient of delay lower than  $-68$  ppm $^\circ\text{C}^{-1}$  was found over the whole range of temperatures. This value is better than in other materials typically used in SAW devices. In conclusion, these studies demonstrate the maturity of AlGaIn for the fabrication of SAW and BAW devices operating at center frequencies over 1 GHz. However, further efforts must be made to reduce the influence of the sapphire substrate on the transfer function and to get the full benefit out of the outstanding physical properties of AlGaIn. Acknowledgements: Thanks are due to Prof. E. Muñoz for his continuous encouragement. Financial support from the Spanish *Ministerio de Ciencia y Tecnología* (Proj. TIC2001-2794) is also acknowledged.

#### 4:40 PM

#### L10, Late News

## Session M: Nitrides: Dislocation Reduction and Characterization

Thursday AM      Room: Lotte Lehmann  
June 27, 2002      Location: University of California

*Session Chairs:* Tom Myers, West Virginia University, PO Box 6315, 224 Hodges Hall, Morgantown, WV 26506 USA; Joan Redwing, Pennsylvania State University, 221 Steidle Bldg., University Park, PA 16802-5006 USA

#### 8:20 AM

**M1, Evolution of Microscopic Growth Domains and Mg Incorporation During Maskless Epitaxial Lateral Overgrowth of AlGaIn on**

**Patterned Sapphire:** *Frank Bertram<sup>1</sup>; J. Christen<sup>1</sup>; A. Bell<sup>2</sup>; R. Liu<sup>2</sup>; Fernando Ponce<sup>2</sup>; H. Amano<sup>3</sup>; I. Akasaki<sup>3</sup>;* <sup>1</sup>Otto von Guericke Universitaet Magdeburg, PO Box 4120, Magdeburg 39016 Germany; <sup>2</sup>Arizona State University, Dept. of Physics & Astron., Tempe, AZ 85287 USA; <sup>3</sup>Meijo University, 1-501 Shiogamaguchi, Tempaku-ku, Nagoya 468-8502 Japan

Maskless epitaxial lateral overgrowth (ELO) of AlGaIn on periodically grooved sapphire has been found to reduce the densities of threading dislocations by two orders of magnitude. Adding Mg was found to extend the lateral growth in GaN. However, the interplay of Al and Mg and their impact on the microscopic growth mechanisms has not been investigated so far. In this paper, the evolution of the self-organized growth domains and their impact on Mg incorporation are investigated by cathodoluminescence microscopy. The sample consists of a (0001)-sapphire substrate, periodically structured into 5  $\mu\text{m}$  wide and 2  $\mu\text{m}$  deep trenches along  $\langle 10\bar{1}0 \rangle$ -sapphire =  $\langle 11\bar{2}0 \rangle$ -AlGaIn direction, with a pitch of 10  $\mu\text{m}$ . After deposition of a LT-AlN nucleation layer the whole structure was overgrown using MOVPE with 6  $\mu\text{m}$  Mg-doped  $\text{Al}_{0.03}\text{Ga}_{0.97}\text{N}$  ( $[\text{Mg}] \sim 10^{19} \text{ cm}^{-2}$ ). Three typical ELO growth domains are present, namely the "seeding" region of coherent growth above the ridges, the ELO wings above the trenches, and the final growth region after reaching coalescence. These ELO growth domains are directly observed by a characteristic modulation of the local CL intensity and wavelength in cross section. No near band edge emission and only a weak and strongly broadened donor-acceptor pair band (DAP) luminescence at  $\sim 3.236$  eV (383 nm) is obtained from the seeding region. The highest CL intensity originates from the ELO wings above the trenches reaching an improvement of two orders of magnitude in integral quantum efficiency. In these regions, a strong and relatively sharp DAP emission is observed, showing a series of well-separated phonon replicas. The high-energy edge is at  $\sim 3.284$  eV (377.7nm) and the energy separation is  $\sim 81$  meV, which correlates well with Mg-related local phonon modes at  $656 \text{ cm}^{-2}$  (81.3 meV). This strongly indicates a local incorporation of Mg as acceptors in the ELO wings, hence maintaining good crystal quality and low compensation. A strong band edge emission peak at 3.476 eV (356.6nm) dominates the center part of the wings. Here, the strain in  $\text{Al}_{0.03}\text{Ga}_{0.97}\text{N}$  is almost completely relaxed. In the upper region of final growth only strongly broadened DAP luminescence is observed at  $\sim 3.173$  eV (391nm), which is completely featureless and shows no phonon replicas. Its intensity and center wavelength is homogeneously distributed over the samples surface. Our CL observations are in perfect agreement with the transmission electron microscopy results. These show a high density of threading dislocations and Mg-precipitates in the seeding and final growth regions and a low defect density and no precipitates in the wings above the trenches. \*Partially supported by the Deutsche Forschungsgemeinschaft and NEDO grant #01-MB10.

#### 8:40 AM

**M2, Facet Controlled Growth in Cantilever Epitaxy for Improved LED Performance:** *Andrew A. Allerman<sup>1</sup>; Daniel D. Koleske<sup>1</sup>; Christine C. Mitchell<sup>1</sup>; Art J. Fischer<sup>1</sup>; David M. Follstaedt<sup>1</sup>; Paula P. Provencio<sup>1</sup>; Nancy A. Missert<sup>1</sup>; Carol H. Ashby<sup>1</sup>;* <sup>1</sup>Sandia National Laboratories, 1126, MS 0601, Albuquerque, NM 87185 USA

The presence of vertical threading dislocations (VTD) can have a significant impact on the optical output power of light emitting diodes (LEDs) operating at UV wavelengths (360-400nm). Many variations of epitaxial lateral overgrowth (ELO) and pendeoepitaxy (PE), which involve multiple growth and masking steps, have been presented as potential ways to achieve low VTD densities ( $<10^8 \text{ cm}^{-2}$ ) over the relatively large areas required for LEDs. Cantilever epitaxy (CE) is a single-growth alternative where GaN growth is nucleated on top of stripes that have been etched out of the substrate (such as sapphire, SiC or Si). GaN growth eventually extends laterally over the etched trench until growth fronts from adjacent stripes coalesce. Like ELO and PE, the material grown between stripes have VTD densities  $<10^6 \text{ cm}^{-2}$  although VTD densities can still exceed  $10^9 \text{ cm}^{-2}$  over the center of the stripes. However, by controlling the initial growth (V/III ratio and/or temperature) on the stripe, we have been able to significantly reduce the dislocation density over the stripe region. This approach is also aided by going to narrower stripe widths ( $< 1 \mu\text{m}$ ) and deeper trenches ( $> 2 \mu\text{m}$ ). Using AFM, SEM, TEM and cathodoluminescence, characterization of the structural and optical properties of CE films, grown with various initial growth conditions, will be presented. LEDs grown on CE substrates with an overall VTD density of  $2 \times 10^8 \text{ cm}^{-2}$  as measured by AFM, have shown improved

output power when compared to LEDs grown on planar sapphire with a VTD of  $10^9 \text{ cm}^{-2}$ . The LED consisted of a 5 quantum well active region ( $40\text{\AA}$ - $\text{In}_{0.04}\text{GaN}$  quantum wells,  $100\text{\AA}$ -GaN barriers) on top of  $3\mu\text{m}$  of Si:GaN. The active region was capped by a  $200\text{\AA}$ , Mg doped  $\text{Al}_{0.17}\text{GaN}$  layer and finally by a  $0.25\mu\text{m}$  Mg:GaN contact layer. An output power of  $1.3\text{mW}$  at  $391\text{nm}$  was measured at  $20\text{mA}$  from LED's grown on a fully coalesced CE-GaN film. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Department of Energy under Contract DE-AC04-94AL85000.

#### 9:00 AM

**M3, Crack-Free Thick AlGaIn Layers Grown on GaN Using Strain-Relief Interlayers:** *Changqing Chen*<sup>1</sup>; Jianping Zhang<sup>1</sup>; Jinwei Yang<sup>1</sup>; G. Simin<sup>1</sup>; M. A. Khan<sup>1</sup>; <sup>1</sup>University of South Carolina, Dept. of Elect. Eng., 300 S. Main St., Columbia, SC 29208 USA

Currently it is becoming more and more important to fabricate optoelectronic devices in deep ultraviolet (UV) region for various applications such as solid-state white light, chemical-biological detection, super high-density storage, fine lithography and flame detection. AlGaIn is the most promising material for deep UV optoelectronics because AlGaIn ternary alloys have direct wide bandgaps ranging from 3.4 to 6.2 eV. The growth of crack-free thick AlGaIn layers with high Al mole fraction on GaN is one of the most fundamental issues in the field of group-III nitrides. In most of III-nitride devices the AlGaIn layer grown on GaN constitutes important component. However, due to excessive tensile strain originating from large lattice-mismatch between GaN and AlN, AlGaIn layer cracks easily with high Al molar fraction. As an example, cracks start to be generated at a thickness of  $0.1 \mu\text{m}$  for  $\text{Al}_{0.15}\text{Ga}_{0.85}\text{In}$  layer if it is grown directly on GaN. These cracks severely deteriorate the performance of the devices. A considerable effort has been made to overcome the cracking problem through the insertion of strain-relief interlayers beneath AlGaIn layers. S. Kamiyama et al. reported the growth of crack-free AlGaIn layers on GaN by a low temperature deposited AlN (LT-AlN) interlayer. By the insertion of the LT-AlN interlayer, we obtained AlGaIn layers with a low density of crack. However, it seems to be still difficult to obtain crack-free high Al content AlGaIn layers by this technique. Very recently, in order to grow a thick crack-free AlGaIn on sapphire, we successfully developed a set of AlN/AlGaIn superlattices (SLs) as interlayers to effectively reduce the biaxial tensile stress. In this work, we report the successful growth of crack-free AlGaIn layers on GaN by combining these two strain-relief techniques together. That is, by using LT-AlN buffer layer and 8 periods AlN/AlGaIn superlattices (SLs) as interlayers, high quality and  $1 \mu\text{m}$ -thick AlGaIn with Al content around 20% without any cracks were deposited on GaN. It has been found that these interlayers not only reduce tensile strain but also decrease dislocation greatly. Using SEM, PL and XRD, the effect of the LT-AlN interlayer and AlN/AlGaIn SLs on the quality of the resulting thick AlGaIn layers has been systematically investigated.

#### 9:20 AM

**M4, Impact of In-Situ  $\text{Si}_x\text{N}_y$  Nano-Masks on Blue GaN Based Light Emitting Diodes on Si(111):** *A. Dadgar*<sup>1</sup>; M. Poschenrieder<sup>1</sup>; O. Contreras<sup>2</sup>; J. Christen<sup>1</sup>; F. Bertram<sup>1</sup>; K. Fehse<sup>1</sup>; J. Blaessing<sup>1</sup>; A. Diez<sup>1</sup>; F. Schulze<sup>1</sup>; F. Ponce<sup>2</sup>; A. Krost<sup>1</sup>; <sup>1</sup>Otto-von-Guericke Universitaet Magdeburg, Fakultat fuer Naturwissenschaften, Magdeburg 39016 Germany; <sup>2</sup>Arizona State University, Dept. of Physics & Astron., Tempe, AZ 85287 USA

We present thick, crack-free GaN based LED structures on Si(111) grown by MOCVD. To reduce tensile stress two low-temperature (LT) AlN:Si interlayers approximately  $10\text{nm}$  thick were inserted in the  $3 \mu\text{m}$  thick diode structure<sup>1</sup>. Further enhancement of the LED structure was achieved by in-situ insertion of a  $\text{Si}_x\text{N}_y$  nano-mask. Transmission electron microscopy measurements show a strong reduction of the threading dislocation density by the LT-AlN as well as the  $\text{Si}_x\text{N}_y$  layers. Cross-sectional cathodoluminescence (CL) microscopy measurements directly evidences a dramatic improvement of optical quality due to the interlayers. The quantum efficiency of the n-GaN more than doubles above each AlN layer. Furthermore an additional gain in CL intensities by a factor of two results for each  $\text{Si}_x\text{N}_y$  interlayer. I-V measurements show a relatively low series resistance which is, despite the large bandgap of AlN, not strongly affected by these layers. Additionally no evidence for a high potential drop at the n-Si/LT-AlN:Si seed layer interface is observed. Current-voltage characteristics of vertically contacted LEDs ( $360 \mu\text{m}$  diameter) with non-optimized contacts show a turn on voltage around  $2.5\text{-}2.8 \text{ V}$  and series resistances of  $55 \text{ W}$ . Blue electroluminescence at  $455\text{nm}$  with

an output power of  $155 \mu\text{W}$  is observed for a simple vertically contacted unstructured diode in an epoxy dome at  $20 \text{ mA}$ . This is already sufficient for simple signaling applications. <sup>1</sup>A. Dadgar, J. Blaessing, A. Diez, A. Alam, M. Heuken, and A. Krost, Jpn. J. Appl. Phys. 39, L1183 (2000).

#### 9:40 AM

**M5, Reducing Threading Dislocations in Laterally Grown GaN: Further Approaches:** *David M. Follstaedt*<sup>1</sup>; P. P. Provencio<sup>2</sup>; C. C. Mitchell<sup>2</sup>; N. A. Missert<sup>2</sup>; C. I. Ashby<sup>2</sup>; D. D. Koleske<sup>2</sup>; Andrew Allerman<sup>2</sup>; <sup>1</sup>Sandia National Laboratories, 1112, MS 1056, Albuquerque, NM 87185 USA; <sup>2</sup>Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185 USA

Reducing threading dislocations in GaN is a key requirement for producing devices with improved performance. Lateral growth methods like Epitaxial Lateral Overgrowth (ELO) and Cantilever Epitaxy (CE) reduce dislocations by reducing the substrate area producing them. CE uses growth on patterned substrates, and has the advantages of requiring a single growth step and avoiding Si autodoping from contact of GaN with barrier layers ( $\text{SiO}_2$  or  $\text{Si}_3\text{N}_4$  in ELO). We have identified two methods to reduce the density of threading dislocations further. First, we initiate growth on narrow mesas  $\sim 1 \mu\text{m}$  wide; during vertical growth with wider mesas, we found that vertical dislocations within  $\sim 0.5 \mu\text{m}$  of the mesa edge would often turn to horizontal, probably due to image forces attracting them to the free surface. Second, we alter the initial vertical growth of GaN to form slanted sidewalls before growing horizontally; dislocations have been shown to turn horizontal when they intersect these slanted surfaces. To check the efficacy of these methods, we examined two CE specimens grown identically except for initial vertical growth geometry: 1) vertical  $\{11\text{-}20\}$  sidewalls, or 2) slanted  $\{11\text{-}22\}$  sidewalls. Sapphire was etched with an inductively coupled plasma to form mesas  $0.6\text{-}0.8 \mu\text{m}$  wide extending along  $[10\text{-}10]$  with trenches  $6 \mu\text{m}$  wide and  $2\text{-}3 \mu\text{m}$  deep between them. MOCVD growth was done with trimethylaluminum, trimethylgallium, and  $\text{NH}_3$  precursors. A  $25\text{nm}$  AlN layer was nucleated at  $480^\circ\text{C}$ , followed growth of  $0.1 \mu\text{m}$  GaN layer at  $1050^\circ\text{C}$ . GaN was then grown vertically to  $0.5 \mu\text{m}$  thickness with vertical or slanted sidewalls at  $1050^\circ\text{C}$  or  $950^\circ\text{C}$ , respectively. Lateral growth followed at  $1080^\circ\text{C}$  to a thickness of  $1.8 \mu\text{m}$ , with additional growth at  $1050^\circ\text{C}$ . Separate specimens were examined by SEM after the vertical growth and showed that the intended sidewall structures had been produced. Cross-section TEM of the full GaN layer over several posts showed that for vertical sidewalls, 30-70% of the dislocations remained vertical and threaded to the surface. In contrast, slanted sidewalls allowed only 2-6% of the dislocations to reach the surface. Thus the second method appears to reduce threading dislocations by an additional order of magnitude. Comparable numbers of dislocations with  $b = a$  and  $b = a + c$  were found, and both turned to horizontal. Cathodoluminescence from GaN at the surface was brighter over the mesas with slanted sidewalls, consistent with fewer threading dislocations. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Department of Energy under Contract DE-AC04-94AL85000.

#### 10:00 AM Break

#### 10:20 AM

**M6, Investigation of the Heteroepitaxial Growth of GaN Directly on SiC(0001) by Plasma-Assisted Molecular Beam Epitaxy:** *Patrick Waltereit*<sup>1</sup>; Sung-Hwan Lim<sup>1</sup>; Melvin McLaurin<sup>1</sup>; James S. Speck<sup>1</sup>; <sup>1</sup>University of California-Santa Barbara, Matls. Dept., Santa Barbara, CA 93106 USA

GaN epilayers usually exhibit a large density of threading dislocations due to lattice-mismatched substrates. These defects deteriorate device performance as they may act as scattering centers in two-dimensional electron gases and leakage paths in vertical devices like light-emitting diodes. Strikingly, there still is only little known about the actual defect generation mechanism for GaN/SiC(0001) despite a rather intense debate on the best growth conditions. In this work, we examine the relationship between growth conditions and defect density as well as the defect generation mechanism for GaN deposited directly on H-etched SiC(0001) by plasma-assisted molecular-beam epitaxy. The samples are characterized by cross-sectional and plan-view transmission-electron diffraction (TEM) and atomic force microscopy (AFM). X-ray diffraction (XRD) rocking curves are carried out in the symmetric (00.2) and the skew-type asymmetric (10.2) reflection. We first studied the impact of different nucleation conditions. Nominally  $10\text{nm}$  thin GaN nucleation

layers were deposited at temperatures between 600°C and 800°C under Ga-lean to Ga-rich surface stoichiometries. These films were investigated by cross-sectional TEM and AFM. The island size increased with substrate temperature and Ga-flux, namely, from about 50nm at 600°C and Ga-lean conditions to about 250nm at 800°C and Ga-rich conditions. Then, we examined epilayers nucleated under the conditions described above but overgrown with 300nm GaN at 720°C under Ga-stable conditions. These samples nucleated at different temperatures clearly show atomic steps as observed by AFM. However, the samples exhibit rather different defect densities as determined by plan-view TEM. The defect density was reduced from 10E11/cm<sup>2</sup> to 10E10/cm<sup>2</sup> with increasing substrate temperature whereas the Ga-flux had only minor impact. The corresponding XRD linewidths decreased with increasing nucleation temperature from approximately 1200 and 2500 arcsec to about 150 and 900 arcsec for the symmetric and asymmetric reflections, respectively. We performed growth-stop experiments in order to study the generation and propagation of dislocations as well as the evolution of surface morphology with film thickness. The samples were deposited according to the conditions yielding the smallest defect density for the 300nm thick films. The thickness was varied from a few nanometers to 2000nm in order to examine the growth transition from isolated islands to completely coalesced films. Currently, the TEM data is consistent with the growth of relaxed, threading dislocation-free islands. It appears that island coalescence is the main source of threading dislocations.

10:40 AM

**M7, Crystalline Qualities and Optical Properties of MBE-Grown GaN/AlN Multiple Quantum Wells for Intersubband Transition:** *Kei Kaneko*<sup>1</sup>; Norio Iizuka<sup>1</sup>; Nobuo Suzuki<sup>1</sup>; <sup>1</sup>Toshiba Corporation, Corporate R&D Ctr., 1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki 212-8582 Japan

Intersubband transition (ISBT) in GaN/AlN or GaN/AlGaIn multiple quantum wells (MQW) is expected to be applicable to ultrafast optical switches because of the very short relaxation time. Although several groups reported ISBT in GaN MQWs, the strain and crystal properties for the MQWs have not been investigated sufficiently. Recently, we achieved ISBT at 1.33-2.17  $\mu\text{m}$  in GaN/AlN MQWs grown by RF-MBE. In present work, we investigated crystalline qualities of the MQWs. The growths were carried out by RF-MBE. The MQWs were grown on the undoped GaN (600 nm) and the AlN buffer layer (50 nm) deposited on a (0001) sapphire substrate. The thickness of the AlN barriers was fixed at 4.5nm. The thickness of the wells (dw) doped with Si at  $8 \times 10^{19}\text{cm}^{-3}$  was 1.25-4.5nm. The number of the wells (Nw) was 30, 120 and 200. First, crystalline qualities were investigated by high-resolution X-ray diffraction ( $2\theta$  scan and reciprocal space mapping [RSM]), PL at 77K and TEM. Clear satellite peaks (-3, -2, -1, 0, +1 order) were observed in  $2\theta/\theta$  scans. The full widths at half maximum (FWHM) of the diffraction from the MQWs with Nw of 120 and 200 were smaller than those for Nw of 30. In PL spectrum, a Stark shift was observed for each sample due to the strain-induced electric fields in the wells. The PL linewidth of the sample with Nw of 120 was about half of those for Nw of 30. This suggests that MQWs with a larger Nw have better crystalline quality. To investigate this, cross-sectional TEM images of the samples were examined extensively. They revealed that dislocations running in the GaN underlying layer upward from the buffer layer tend to slant slightly at the GaN/AlN interface and merge together. The MQWs with many interfaces were proven to be effective for reducing the dislocation density. Good periodicity with about  $\pm 1$  monolayer interface fluctuation was also confirmed for MQWs with Nw of 120 and 200. Next, strain in the sample was evaluated by RSM for GaN (11-24) reflection. The results indicate a full lattice relaxation in the MQWs. This is in contrast to the case for MOCVD-grown GaN/Al<sub>0.65</sub>Ga<sub>0.35</sub>N MQWs, where the MQWs were grown coherently on GaN. This is considered to be related to the difference of dislocation density among them. In conclusion, we have investigated crystalline qualities of the MBE-grown GaN/AlN MQWs. It was found that dislocation density is decreased in the MQWs with lattice relaxation. This work was performed under the management of the Femtosecond Technology Research Association, which is supported by the New Energy and Industrial Technology Organization.

11:00 AM

**M8, Dislocation Density and Electrical Compensation in GaN Films:** *Mark E. Twigg*<sup>1</sup>; Alma E. Wickenden<sup>2</sup>; Daniel D. Koleske<sup>3</sup>; Richard L. Henry<sup>1</sup>; Steven C. Binari<sup>1</sup>; Paul B. Klein<sup>1</sup>; <sup>1</sup>Naval Research Laboratory, Elect. Sci. & Tech. Div., Code 6812, Washington, DC 20375-5320 USA;

<sup>2</sup>Army Research Laboratory, Micro Devices Branch, Adelphi Rd., Adelphi, MD 20783 USA; <sup>3</sup>Sandia National Laboratories, Cheml. Processing Sci. Dept., MS 0601, Albuquerque, NM 87185 USA

In order to serve as the basis for AlGaIn/GaN HEMT RF microwave devices, III-nitride films must be highly resistive. To this end we have studied the influence of extended defects on electrical resistivity in MOCVD nitride films grown on a-plane sapphire substrates using a close-coupled showerhead (CCS) reactor and an AlN nucleation layer (NL). One approach to achieving compensation of shallow donors in nitride films is to control the density of edge dislocations (acting as deep acceptors). We have found that the resistivity of GaN films increases exponentially with the edge dislocation density (as determined from plan-view TEM measurements). The density of edge dislocations in GaN films is controlled by grain nucleation during high temperature (HT) growth. Although the edge dislocation density must be held below a certain level ( $\sim 3 \times 10^9/\text{cm}^2$ ) to insure high electron mobility, edge dislocation density must also be high enough to allow proper compensation of shallow donors. In order to control grain nucleation and edge dislocation density, however, it is necessary to control the structure of the AlN NL which serves as the growth template. Using cross-sectional TEM (XTEM), we have found that a defective NL has few nucleation sites for HT growth, and as a result defective NLs give rise to GaN films with low edge dislocation density as well as low resistivity. Conversely, a less-defective NL has many good nucleation sites for HT growth, and gives rise to GaN films with a higher edge dislocation density as well as higher resistivity. HRTEM observations indicate the defective NLs in low-resistivity films are due to a rough NL/sapphire interface, whereas the less-defective NLs in high-resistivity films correspond to a smoother NL/sapphire interface. The NL/sapphire interface that figures so significantly into GaN resistivity can be ascribed, in turn, to the interplay between the surface morphology of the as-received sapphire wafer and nitridation immediately prior to NL growth. Whereas moderate nitridation reduces the roughness of the sapphire surface, excessive nitridation enhances substrate roughness. The key to controlled growth is then as many have argued: a proper control of sapphire nitridation. We have found, however, that the structural effects of nitridation can be easily monitored by XTEM of easily cleaved samples, so that weak-beam dark field XTEM observations can be used to determine the defect density of the NL as well as the likelihood that the film will be sufficiently resistive for HEMT devices.

11:20 AM Student

**M9, Limitation of the Lattice Thermal Conductivity of GaN Films by Threading Dislocations and Point Defects:** *Jie Zou*<sup>1</sup>; Dmitri Kotchetkov<sup>1</sup>; Alexander Balandin<sup>1</sup>; <sup>1</sup>University of California-Riverside, Dept. of Elect. Eng., Riverside, CA 92521 USA

Proposed applications of GaN-based devices as laser diodes, microwave power sources and ultra-high power switches rely heavily on the possibility of removing high density of excess heat from the device active area. Both the material of the active layer and the substrate material generally determine the thermal resistance of the device structure. Thus, it is important to know the values of thermal conductivity of corresponding materials in order to perform heat spreading simulations and obtain thermal constraints on the device design. The initial measurements of the thermal conductivity  $k$  of GaN films grown by hydride vapor phase epitaxy revealed a rather low value of about 1.3 W/cm-K at room temperature. More recent investigations indicated higher values: from 1.55 W/cm-K to 2.1 W/cm-K in lateral epitaxial overgrown GaN films with low dislocation density. In this paper we will report results of the theoretical investigation of the lattice thermal conductivity in wurtzite GaN. The specific goal of our investigation is to clarify the role of threading dislocations and point defects in limiting the room-temperature thermal conductivity of GaN films. Numerical simulations are performed for n-type wurtzite GaN with different density of silicon dopants, point defects and threading dislocations. It was found that thermal conductivity is sensitive to density of dopants and dislocations: an increase in the doping density from  $1 \times 10^{17} \text{ cm}^{-3}$  to  $1 \times 10^{18} \text{ cm}^{-3}$  with corresponding increase in the carrier concentration leads to a decrease in the lattice thermal conductivity from 1.41 W/cm-K to 0.77 W/cm-K. A decrease in the dislocation density by two orders of magnitude in GaN leads to a corresponding increase of the thermal conductivity from 1.31 W/cm-K to 1.97 W/cm-K. If the dislocation density is low (well below  $1 \times 10^{10} \text{ cm}^{-2}$ ), the thermal conductivity becomes independent of the dislocation density and is mostly determined by phonon Umklapp scattering and point defects (including

dopants). Our theoretical predictions are in good agreement with experimental data. The proposed model can be used for accurate simulation of self-heating effects in GaN-based power devices.

#### 11:40 AM Student

**M10, Determination by Electron Holography of the Charge Distribution in Threading Dislocations in Epitaxial GaN:** *Juan Cai*<sup>1</sup>; Fernando A. Ponce<sup>1</sup>; <sup>1</sup>Arizona State University, Dept. of Physics & Astron., Box 871504, Tempe, AZ 85287-1504 USA

GaN epitaxy is usually associated with high density of threading dislocations ranging from  $10^8$  to  $10^{11}$  cm<sup>-2</sup>. Although structural microanalysis by transmission electron microscopy (TEM) can easily identify them to be of the edge, screw or mixed types, little is known about their charge states. Electron holography is able to profile the potential across the dislocations by producing an interference pattern between the beam going through the sample and a reference beam traveling through vacuum. In this work, electron holography is applied to different types of threading dislocations in an undoped GaN film. The film was grown on c-plane sapphire by metalorganic chemical vapor deposition (MOCVD). From the holograms, the potential profiles are deduced, and the charge distributions are determined by use of Poisson's equation. The potential profiles show that all types of dislocations are negatively charged. The line charge density in the dislocation core, defined by  $n$  electrons per unit cell along the  $c$  direction, is determined. The line charge density for edge, screw and mixed dislocation is  $\sim 0.3e/c$ ,  $1e/c$ , and  $0.6e/c$ , respectively. The influence of the experimental conditions, such as the tilting angle, on the charge densities is explored. We found that the experimentally determined charge density in the dislocation core does not change significantly with the tilting angle.

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## Session N: Photonic Bandgap Materials and Devices

Thursday AM      Room: MultiCultural Theatre  
June 27, 2002      Location: University of California

*Session Chairs:* Laura Wills Mirkarimi, Agilent Technologies, Inc., Bldg. 26M-7, 3500 Deer Creek Rd., Palo Alto, CA 94304 USA; Julia W.P. Hsu, Lucent Technologies, 600 Mountain Ave., Rm. 1D-368, Murray Hill, NJ 07974 USA

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#### 8:20 AM Invited

**N1, Dispersion and Dispersion Control in Photonic Crystals:** *Shanhui Fan*<sup>1</sup>; Zheng Wang<sup>2</sup>; <sup>1</sup>Stanford University, Dept. of Elect. Eng., Stanford, CA 94305-4088 USA; <sup>2</sup>Stanford University, Appl. Physics, Ginzton Lab., Stanford, CA 94305-4088 USA

Photonic crystals are very well known for their capability of generating strong group velocity dispersion and group delay. However, much less is known about how to engineer the crystal structures to generate the form of dispersion needed for applications such as optical communications. Simple periodic structures give rise to group velocity dispersions that vary rapidly over small spectral or angular ranges, while many applications would want, for example, a linear variation of group velocity over a larger range for a wavelength dispersive element, or a constant delay over a sufficiently large bandwidth for delaying an optical pulse without distorting it. In this talk, we will discuss the physical principles and the design of crystal structures for dispersion control purposes.

#### 9:00 AM Invited

**N2, On-Chip Assembly of Silicon Photonic Band Gap Crystals:** *David J. Norris*<sup>1</sup>; <sup>1</sup>University of Minnesota, Dept. of Cheml. Eng. & Matls. Sci., Minneapolis, MN 55455 USA

Photonic crystals, structures that are periodic on an optical length scale, can reflect light for any direction of propagation. Since this property, known as the photonic bandgap, can be utilized to confine, manipulate, and guide photons, photonic bandgap crystals should enable a variety of optical devices all combined on an ultra-compact optical chip. For this goal, conventional semiconductor nanofabrication techniques have been adapted to make photonic crystals. However, a potentially simpler and cheaper approach for creating three-dimensionally periodic (3D)

structures is the natural assembly of colloidal microspheres. Unfortunately, despite recent successes in achieving semiconductor photonic crystals with this approach, strong skepticism remains whether such crystals will ever be useful. Natural assembly not only yields irregular, polycrystalline photonic crystals that are impossible to incorporate into a device, but more importantly, it leads to many defects that destroy the photonic bandgap. Here, these issues will be addressed by exploring high-quality silicon inverted opals that are assembled directly "on-chip". Optical results show that the defect densities in these structures are sufficiently low that the photonic bandgap survives. Further, since the photonic crystal is grown directly onto a Si wafer, we demonstrate that it can be subsequently patterned for a desired device application with straightforward post-growth processing. Our approach, while retaining the simplicity of natural assembly, provides structures that reclaim many of the advantages of conventional nanofabrication.

#### 9:40 AM

**N3, Creating Periodic 3D Structures by Multi-Beam Interference:** *Shu Yang*<sup>1</sup>; Mischa Megens<sup>1</sup>; Joanna Aizenberg<sup>1</sup>; Pierre Wiltzius<sup>2</sup>; Julia Hsu<sup>1</sup>; Frederik Schrey<sup>1</sup>; Paul M. Chaikin<sup>3</sup>; William B. Russel<sup>4</sup>; <sup>1</sup>Lucent Technologies, Bell Labs., 600 Mountain Ave., Murray Hill, NJ 07974 USA; <sup>2</sup>University of Illinois at Urbana-Champaign, Beckman Inst., 405 N. Mathews, Urbana, IL 61801 USA; <sup>3</sup>Princeton University, Dept. of Physics, Princeton, NJ 08554 USA; <sup>4</sup>Princeton University, Dept. of Cheml. Eng., Princeton, NJ 08554 USA

Photonic crystals that could reflect light incident from any direction have driven extensive research effort to explore novel materials and fabrication process. However, it remains technologically challenging to rapidly create highly ordered three-dimensional structures with sub-micron periodicities and to comply with demands, such as controlling defects in a large area and fabrication at low cost. Self-assembly of block copolymers, colloidal crystals and sol-gel process are found to be simple and fast, yet random defects are inevitable in a large area. Two-photon absorption at near-IR and multi-beam interference of UV light on photosensitive materials are promising lithographic techniques to construct 3D structures defect-free. However, the pinpoint writing in two-photon process may not be suitable for massive production. The reproducibility of interference pattern using a pulsed laser and the efficiency of UV light penetration in a thin film may limit the broader application of the multi-beam interference method. Based on photosensitized cationic polymerization of epoxy (SU-8), we fabricated a series of 2D and 3D defect-free porous structures, using interference of three or four beams of visible laser in a continuous wave (cw) mode. An appropriate concentration of amine is added to eliminate non-zero background caused by polarization of multiple beams. Films with thickness ranging from 4 to 10 micrometers were prepared by spin-coating or casting on the substrate. The exposure was conducted on a horizontal stage with three or four non-coplanar beams of an Argon ion laser for  $\sim 1$  s. The laser generated 514nm light in a continuous wave and provided a stable output of  $1 \text{ J/cm}^2$ . The beam diameter was approximately several millimeters. The relatively high glass transition temperature ( $T_g$ ) of SU-8 plays an important role to minimize the acid diffusion before post-exposure bake. Thus, the photopolymerization is separated from exposure steps without disturbing the interference patterns. After removing the unexposed film by organic solvents, completely opened holes with hexagonal and face centered cubic symmetries were obtained with periods of  $\sim 1$  micrometer in an area larger than 0.1 mm. These porous structures can serve as templates to fill high index materials for reversed 3D photonic crystals. In addition, we found that these materials could also be photopolymerized by two-photon absorption at 700nm. The capability to combine both multi-beam interference and two-photon absorption provides advantage to create a 3D structure with controlled defects. This imaging method paves a new way to microfabricate 3D structures and is applicable to a wide range of photosensitive materials to engineer the photonic structures.

#### 10:00 AM Break

#### 10:20 AM Invited

**N4, 2-D Unit-Cell Photonic Band Gap Nanolasers:** *Y. H. Lee*<sup>1</sup>; J. K. Hwang<sup>1</sup>; H. Y. Ryu<sup>1</sup>; H. K. Park<sup>1</sup>; <sup>1</sup>Korea Advanced Institute of Science and Technology, Dept. of Physics, 373-1 Kusung-dong, Yusung-gu, Taejeon 305-701 Korea

Recently 2-D photonic bandgap structures have produced a great

deal of interesting results due to the advancement of nanofabrication technologies. Here, we present and optical characteristics of two types of novel 2-D photonic crystal lasers that are candidates of ultimate thresholdless lasers. The 2-D photonic crystal lasers are realized on the free-standing InGaAsP slab waveguide structure. As an active layer, six compressively strained (0.6%) InGaAsP quantum wells are used. The compressive strain at the quantum wells splits the heavy hole band and light hole band and the coupling to the TM mode is discouraged. The laser cavities are optically pumped normal to the structure using a 980-nm InGaAs laser. As a first form of PBG lasers, the modified unit cell monopole mode laser realized on triangular lattice 2-D photonic crystal is discussed. This monopole mode is characteristically nondegenerate and is derived into the photonic bandgap from the 'conduction' band. As the other form of PBG lasers, the PBG laser built on a square lattice 2-D photonic crystal will be discussed. This unit cell square lattice PBG laser operates in a mode reminiscent of the smallest possible whispering gallery mode. Interestingly, the mode has very large quality factor  $>30,000$  and mode volume much smaller than the conventional microdisk laser. Both unit cell PBG nanolasers have low threshold of  $<0.5$  mW incident. Moreover, since both nanocavity modes have intensity nodes at the center of the cavity where small post can be inserted with minimal degrading of the Q factor. Therefore, these structures are good candidates for electrically-driven ultralow-threshold PBG nanolasers. This work was supported by National Laboratory Project of Korea and Office of Naval Research.

**11:00 AM Invited**

**N5, Promises of Photonic Crystals Revisited: The Case of III-V 2D Photonic Crystals:** *Claude Weisbuch*<sup>1</sup>; <sup>1</sup>Ecole Polytechnique, Lab PMC, Palaiseau 91120 France

The successful implementation of III-V semiconductor devices in wide-scale photonic markets requires to reach at least some highly desired features such as efficiency/compactness/functionality/integration/manufacturability/cost. In the past few years, several 3D fabrication techniques have been demonstrated which lead/should lead to the observation of full 3D bandgaps. However, 3D PCs do not easily yield sizeable physical effects such as the control of spontaneous emission or lifetime changes, or in structures that could be exploited in the optoelectronics field. On the other hand 2D PCs in thin-slab or waveguide structures open a number of new possibilities in optoelectronics or in the realization of various integrated optics components such as mirrors, micro-resonators, couplers, etc. In that case waveguiding in the third direction orthogonal to the PC design leads to full 3D confinement of optical modes. Earlier physics studies consisted in establishing the basic kinematic properties of 2D PCs such as transmission, reflexion and diffraction coefficients. It is now well established that for a variety of structures and materials excellent, quasi-intrinsic properties can be obtained<sup>1</sup>. To further assess the potential of 2D PCs in optoelectronics applications, it is essential to evaluate in-depth radiation losses in the substrate or superstrate around the slab. They represent an unwanted loss mechanism for resonator or integrated optics purposes, or a welcome extraction mechanism for light in LEDs. We have developed an analytical methods which gives, as a function of the basic system parameters (hole diameter and height, index contrasts of super- and sub-strate with respect to the core), an imaginary index of refraction in the air holes representing radiative losses, in excellent agreement when compared with exact 3D calculations or to quantitative experimental results<sup>2</sup>. Building blocks for photonic integrated circuits have been studied. Various waveguides can be designed, with "acceptable" propagation losses. Very high-performance devices can be foreseen from the measured quality factors of microcavities in excess of 1000. The coupling of a photonic crystal bounded waveguide and hexagonal PC microcavities opens the way to add-drop filters<sup>3</sup>. Losses can be engineered towards useful applications concepts. We have recently used new PC structures to yield LEDs with ultimate emission efficiencies, although with a fully planar process. It thus appears that photonic crystals might have a huge impact in various essential areas of future technologies, although not exactly in the way originally predicted. <sup>1</sup>H. Benisty et al., J. Lightwave Techn. 17, 2063, 1999; <sup>2</sup>H. Benisty et al., Appl. Phys. Lett., vol. 76, 532, 2000; <sup>3</sup>C. J.M. Smith et al., Appl. Phys. Lett. 78, 1487, 2001.

**11:40 AM**

**N6, High Accuracy FDTD Calculation of Pulse Compression in a Finite Photonic Crystal Waveguide:** *James B.B. Cole*<sup>1</sup>; Shigeki Yamada<sup>2</sup>;

Yoshifumi Katayama<sup>2</sup>; <sup>1</sup>University of Tsukuba, Inst. for Info. Sci., Tennodai 1-1-1, Tsukuba, Ibaraki 305-8573 Japan; <sup>2</sup>University of Tsukuba, TARA Ctr., Tennodai 1-1-1, Tsukuba, Ibaraki 305-8577 Japan

The Finite-Difference Time-Domain (FDTD) method of the Yee algorithm is a powerful tool to solve Maxwell's equations in complicated geometries. Because the electromagnetic fields are marched in time, pulses and other transients can be easily modeled. Unfortunately, however, accuracy is only second order. The solution error is  $\tilde{a} \sim (h/\tilde{\epsilon})^2$ , where  $\tilde{\epsilon}$ =wavelength, and  $h$  is the grid spacing. Halving  $h$ , reduces  $\tilde{a}$  by a factor of four, but the number of space-time grid points rises by a factor of 16 (because the time step  $\sim h$ ). Thus the price of high accuracy is very large computational cost. Higher order finite differences could be used to increase accuracy, but computational costs are still high, and the algorithm is greatly complicated. By replacing the finite differences of the Yee algorithm with what are called nonstandard finite differences (NSFD), the error can be reduced to  $\tilde{a} \sim (h/\tilde{\epsilon})^6$ , at constant frequency. High accuracy alone is not enough. In addition, a good computational model is needed. Such problems as how to model circular holes on a square grid centered at arbitrary positions between the grid points, how to terminate the computational region, and what kind of input signal to use must be addressed. Although these problems per se have been solved, it is a challenge to integrate their solutions into a robust model that yields results that are insensitive to the model parameters. For scattering off a cylindrical hole we found that when wavelength-radius ratio is  $\tilde{\epsilon}/r \sim 8$ , the scattering is insensitive to the exact shape, so long as the integral of refractive index over the hole's area is correctly represented. This is because as  $\tilde{\epsilon}/r$  increases the scattering transitions from the Mie regime to Rayleigh scattering. We developed computational models of both pulsed and continuous gaussian beams incident on a photonic crystal consisting of circular air holes in a dielectric substrate, arranged in a hexagonal lattice. We took lattice constant to be  $a = 83\text{nm}$ , and the hole radius to be  $r = 0.4a$  in a substrate of refractive index  $n = 3.45$ . The vacuum wavelength was  $\tilde{\epsilon} = 1,550\text{nm}$ . Using our NSFD-Yee algorithm we computed the transmission spectra and electromagnetic modes of various finite photonic crystals, and compared our results with a supercell method (that assumes infinite periodicity) and found excellent agreement. We formed a waveguide by deleting a line of holes in a  $10 \times 10$  array, and computed its transmission spectrum and simulated propagation of chirped pulses in the waveguide. We were able to directly infer group velocity,  $d\tilde{\omega}/dk$ , and the dispersion,  $d^2\tilde{\omega}/dk^2$ , in the waveguide ( $\tilde{\omega}$ =angular frequency,  $k$ =wavenumber). Our simulations demonstrated that this small waveguide yields pulse compression. Furthermore our FDTD calculations of  $d\tilde{\omega}/dk$ , and  $d^2\tilde{\omega}/dk^2$  agreed almost exactly with supercell band calculations.

## Session O: Gate Dielectrics - I

Thursday AM  
June 27, 2002

Room: UCEN State Street  
Location: University of California

*Session Chairs:* Darrell Schlom, Pennsylvania State University, 108 MRI Bldg., Research Park, PA 16803-6602 USA; Pat Lenahan, Pennsylvania State University, 227 Hammond Bldg., University Park, PA 16802 USA

**8:20 AM Invited**

**O1, Interface and Materials Properties of High-K Gate Stack Structures:** *Eric L. Garfunkel*<sup>1</sup>; Torgny Gustafsson<sup>2</sup>; Hartmut Schulte<sup>2</sup>; <sup>1</sup>Rutgers, The State University of New Jersey, Chem., 610 Taylor Rd., Piscataway, NJ 08854 USA; <sup>2</sup>Rutgers, The State University of New Jersey, Physics, 136 Frelinghuysen Rd., Piscataway, NJ 08854 USA

In this work we describe recent results using medium energy ion scattering (MEIS), synchrotron based photoemission (SXPS), inverse photoemission (IPE), and electron microscopy (TEM) to examine various metal oxide gate dielectrics and their interfaces with silicon and metal layers. The SXPS and IPE results are used to determine the density of states above and below the Fermi energy; this information is very helpful in understanding threshold voltages and leakage. We find that the densities of states at the band edges (in particular band tail states) make the

assignment of a simple threshold voltage somewhat problematic. We present new ion scattering results on interface stability in several gate structures at elevated temperature. Interesting electrical and materials behavior occurs during post-processing at elevated temperature. We observe that oxygen diffuses to the metal oxide-silicon interface forming an SiO<sub>2</sub> film whose thickness is limited primarily by the temperature of the process and the pre-existing SiO<sub>2</sub> thickness. Our model is that the metal oxide catalytically dissociates molecular oxygen, incorporating excess atomic oxygen into the metal oxide lattice that diffuses toward the SiO<sub>2</sub>/metal oxide interface forming new SiO<sub>2</sub>. The excess SiO<sub>2</sub> that is formed at the interface reduces the interface electrical defect concentration but lowers the overall capacitance. We also present a model of oxygen removal via SiO desorption during elevated temperature. These and other data are presented with special reference to how processing parameters effect interface composition and electrical behavior.

#### 9:00 AM

##### **O2, Layered Tunnel Barriers for Silicon Based Nonvolatile Memory**

**Applications:** Julie D. Casperson<sup>1</sup>; L. D. Bell<sup>2</sup>; Brett W. Busch<sup>3</sup>; Lalita Manchanda<sup>3</sup>; Martin L. Green<sup>3</sup>; Harry A. Atwater<sup>1</sup>; <sup>1</sup>California Institute of Technology, MS 128-95, 246 Watson Lab., Pasadena, CA 91125 USA; <sup>2</sup>Jet Propulsion Laboratory, USA; <sup>3</sup>Agere Systems, Bell Labs., 600 Mountain Ave., Murray Hill, NJ 07974-2008 USA

Among the main performance limitations of floating gate nonvolatile memory devices, such as flash memories and nanocrystal memories, are the long program time (~1 s) and erase time (~1 ms) achievable via a Fowler-Nordheim tunneling mechanism for charging of the floating gate through a homogeneous tunnel barrier. An interesting alternative to homogeneous dielectric tunnel barriers is a silicon compatible layered tunnel barrier, which enables a large drop in the barrier height with applied voltage. To assess the performance of layered tunnel barriers, we have performed simulations and experiments with heterostructure amorphous dielectrics on Si(100). Tunneling probability simulations for these barriers have been performed numerically using a coupled Poisson-Schrödinger model in the effective-mass approximation. Using this model we have calculated the current-voltage (I-V) characteristics so that we can optimize the layered tunnel barrier structure. Ideally we would like the ratio of the current density at some maximum voltage to the current density at some minimum voltage to be at least as large as 1018 to correspond to a device with a retention time of at least 30 years and a programming time of about 1 nanosecond. In Fig. 1, four simulated I-V curves for theoretical barrier structures that closely approximate a perfectly graded barrier are shown. A graded triangular barrier structure is indicated by the solid curve. The 5-layer structure (dotted line) has tunneling characteristics that very closely approximate the continuously graded barrier. The three-layer structure (dashed line) still approximates the graded structure, but differs more than the 5-layer structure. A homogeneous barrier has characteristics that are considerably different from the graded and layered barriers exhibiting an electron tunneling current density at V = 4 V that is approximately 1011 times lower. Curves such as these emphasize the ability of layered structures to significantly increase the tunneling current ratios compared with the square barriers that are used in devices today. We have done extensive simulation to analyze possible structures with real materials parameters. We found that one of the most promising structures for layered tunnel barriers consists of Si<sub>3</sub>N<sub>4</sub> and Al<sub>2</sub>O<sub>3</sub> with assumed conduction band offsets of 2.4 eV and 2.8 eV, respectively, and we have fabricated such structures. The Si<sub>3</sub>N<sub>4</sub> was made by low-pressure chemical vapor deposition, and the Al<sub>2</sub>O<sub>3</sub> was made by atomic layer deposition. A comparison of the current-voltage and capacitance-voltage characteristics of these types of structures will be discussed as well as the structural characterization. Figure 2 shows an important experimental current-voltage result where we compare the symmetry of a two-layer and three-layer structure. We find significant asymmetry in the two-layer measurement, indicating for the first time barrier lowering in a Si-based layered tunneling barrier structure.

#### 9:20 AM

**O3, Structure and Stability of Alternative High-K Dielectric Layers on Silicon:** Susanne Stemmer<sup>1</sup>; Zhiqiang Chen<sup>1</sup>; Dmitri Klenov<sup>1</sup>; Dong Niu<sup>2</sup>; Gregory Parsons<sup>2</sup>; Jon-Paul Maria<sup>3</sup>; Angus I. Kingon<sup>4</sup>; <sup>1</sup>Rice University, Mechl. Eng. & Matls. Sci., MS-321, Houston, TX 77005-1892 USA; <sup>2</sup>North Carolina State University, Dept. of Cheml. Eng., Stinson Dr., Raleigh, NC 27695-7905 USA; <sup>3</sup>North Carolina State University, Dept. of Matls. Sci. & Eng., 1010 Main Campus Dr., Raleigh, NC 27695

USA; <sup>4</sup>North Carolina State University, Matls. Rsrch. Ctr., 1001 Capability Dr., Centennial Campus, Raleigh, NC 27695-7919 USA

Integration of alternative high-K dielectric layers in real CMOS devices requires a number of stability problems associated with high-temperature device processing to be resolved. Stability problems include interdiffusion, phase separation, crystallization and reactions. High-K layers are typically thin (~ 2nm) and amorphous, and require a characterization method that can investigate their composition on the atomic scale. We use electron energy-loss spectroscopy (EELS) in scanning transmission electron microscopy with a sub-0.2 nm probe and atomic resolution transmission electron microscopy to investigate Y<sub>2</sub>O<sub>3</sub>, ZrO<sub>2</sub> and HfO<sub>2</sub> based layers. In Y<sub>2</sub>O<sub>3</sub> we show that untreated Si substrates cause silicate formation at high temperatures whereas nitrogen plasma pre-treated Si surfaces successfully prevent Si diffusion from the substrate during high temperature anneals. We show that the reaction with Si is self-limiting, and we investigate the role of crystallization of the binary oxide in this reaction. For ZrO<sub>2</sub> thin films we show that annealing under reduced oxygen partial pressures can prevent extensive SiO<sub>2</sub> formation at the interface, which is typically observed under uncapped annealing conditions, when residual oxygen is present in the annealing atmosphere. At even lower oxygen partial pressures (about 10<sup>-7</sup> torr), silicide formation at the interface is observed, as expected from thermodynamic calculations. Our results show that oxide crystallization is important in determining the overall phase formation behavior. We also show that capping during annealing can successfully prevent the formation of interfacial SiO<sub>2</sub>.

#### 9:40 AM Student

**O4, Radiation Induced Interface Traps in MOS Devices: Capture Cross Sections and the Density of States of P<sub>bi</sub> Silicon Dangling Bond Centers:** Nathaniel A. Bohma<sup>1</sup>; Jason P. Campbell<sup>1</sup>; Patrick M. Lenahan<sup>1</sup>; <sup>1</sup>Pennsylvania State University, Eng. Sci. & Mech., 212 Earth & Eng. Sci. Bldg., University Park, PA 16802 USA

Si/SiO<sub>2</sub> interface traps are dominated by silicon dangling bond defects called P<sub>b</sub> centers. The P<sub>b0</sub> center is well understood, but the P<sub>bi</sub> center remains extremely controversial. Early results of Gerardi *et al* and recent results of Mishima *et al* indicate that P<sub>bi</sub> centers are interface trap centers with levels near the middle of the band gap. However, Stesmans and Afanas'ev argue that the P<sub>bi</sub> center has no levels in the gap and that, in fact, the (100) Si/SiO<sub>2</sub> interface dominates MOS technology because of the electrical inactivity of the P<sub>bi</sub> center. In this study we compare the two most important "electronic" aspects of the fairly well understood P<sub>b0</sub> and the as yet controversial P<sub>bi</sub>: the density of states and capture cross sections. With spin dependent recombination (SDR) we can compare the capture cross-section of the P<sub>bi</sub> center to that of the well understood P<sub>b0</sub> center defect. This measurement is only sensitive to charge capture by the centers in the neutral state, for example the capture of an electron by a neutral P<sub>b0</sub> center. A direct comparison of the capture cross sections of several traps in the same device can be obtained by making SDR measurements with variable audio frequency modulation of the large magnetic field. We have made such measurements on a device with comparable P<sub>bi</sub> and P<sub>b0</sub> densities. Note the very similar response of the P<sub>b0</sub> and P<sub>bi</sub>. The results indicate quite similar capture cross section for the two centers. We have compared the P<sub>bi</sub> and P<sub>b0</sub> densities of states using conventional ESR measurements versus applied voltage on quite thin 3.3nm oxides on silicon. By measuring the fraction of P<sub>b0</sub> and P<sub>bi</sub> centers with an unpaired electron as a function of surface potential we can obtain a rough measurement of the density of states of the centers. We compare the P<sub>b0</sub> and P<sub>bi</sub> response on a Si/SiO<sub>2</sub> structure in which both centers are present at approximately equal densities. A plot of P<sub>b0</sub> and P<sub>bi</sub> ESR amplitude versus bias is shown in figure 2. The P<sub>bi</sub> signal appears over a narrow range of bias over which the Si/SiO<sub>2</sub> Fermi level is fairly near the middle of the silicon bandgap. The P<sub>bi</sub> amplitude curve is quite a bit narrower than that of P<sub>b0</sub>. The P<sub>bi</sub> curve is also shifted negatively with respect to the P<sub>b0</sub> curve. The results allow us to draw several conclusions with regard to the P<sub>bi</sub> density of states. The P<sub>bi</sub> electron correlation energy is about half that of P<sub>b0</sub>. The P<sub>bi</sub> density of states is skewed ~0.2 eV below the center of the P<sub>b0</sub> distribution, clearly toward the lower half of the Si band gap.

#### 10:00 AM Break

#### 10:20 AM

**O5, Thermally Stable Single Layer Hafnium Silicate Films for Gate Dielectric Application:** S. Gopalan<sup>1</sup>; C. S. Kang<sup>1</sup>; R. Nieh<sup>1</sup>; R. Choi<sup>1</sup>; K.

Onishi<sup>1</sup>; H.-J. Cho<sup>1</sup>; S. Krishnan<sup>1</sup>; J. C. Lee<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Microelect. Rsrch. Ctr., MC R9950, Austin, TX 78758 USA

In the last few years, research on high-k materials for gate dielectric application has expanded significantly and has helped to narrow down the available choices. HfO<sub>2</sub>, ZrO<sub>2</sub>, and their silicates are amongst the prime candidates for this application. Although HfO<sub>2</sub> has many excellent electrical characteristics, it also suffers from disadvantages such as low crystallization temperatures, large interfacial layer growth at high temperatures, and reliability issues such as boron penetration effects. It is believed that use of Hf-silicate can alleviate many of these problems to a large extent. In this work, we have obtained high quality Hf-silicate films with EOT as low as 10.7Å. The films are thermally stable and are compatible with polysilicon gate as well. For TaN gate process, after defining active regions Hf and Si were co-sputtered in Ar ambient at room temperature. Ex-situ furnace annealing (post deposition annealing, PDA) was done at 600°C in N<sub>2</sub> ambient for 2.5 minutes. After depositing TaN by DC sputtering, capacitors were defined by patterning TaN followed by RIE. For polysilicon gate process, co-sputtering of Hf and Si was done after surface pre-treatment using NH<sub>3</sub> at 700°C for 25 seconds. After ex-situ furnace annealing at 600°C for 2.5 minutes, LPCVD poly (2000Å) was deposited at 580°C. Gate regions were defined by wet etching of polysilicon. Implantation of G/S/D was done simultaneously using P. Following LTO deposition and contact formation, dopant activation was done by RTA in N<sub>2</sub> ambient (950°C). Sintering was done at 450°C in forming gas for 20 minutes after Al metallization. Film composition was determined using XPS. EOT was determined from accumulation capacitance of capacitor CV (@ 1MHz). Fig. 1 shows the equivalent oxide thickness (EOT) versus leakage density for HfO<sub>2</sub> and Hf-silicates of various compositions. It is seen that irrespective of composition, the distribution for Hf-silicate is very similar to that of HfO<sub>2</sub>. We believe that this is probably due to similar SiO<sub>2</sub>-type interfacial layer for both materials. This also indicates the impact of interfacial layer on the electrical characteristics. Fig. 2 shows typical C-V characteristics of TaN/silicate/p-Si structures. Well-behaved C-V profiles with excellent dispersion characteristics and EOT as low as 10.7 Å were obtained. For the same film, the leakage at -1.5V was found to be ~1mA/cm<sup>2</sup>. The interface state density as determined by the Terman method was found to be < 8 x 10<sup>10</sup> eV<sup>-1</sup> cm<sup>-2</sup>. We also observed that with higher Si content in the silicate, the thermal stability also improved (data not shown). Fig. 3 shows the high-resolution TEM micrographs of Poly/silicate (13%Si)/p-Si structures. It can be observed that the silicate remains stable and amorphous even after a 950°C anneal. No top interfacial is observed and the bottom interfacial layer is only around 6-7 Å. Very good transistor characteristics were also obtained with polysilicon gate.

10:40 AM

O6, Late News

## Session P: Quantum Wells & Superlattices

Thursday AM      Room: UCEN Harbor  
June 27, 2002      Location: University of California

*Session Chairs:* Mark Miller, University of Utah, 122 S. Central Campus Dr., Rm. 304, Salt Lake City, UT 84112-0506 USA; Ben Shanabrook, Naval Research Laboratories, Nanostructures Section, Code 6870, Washington, DC 20375-5000 USA

8:20 AM Invited

**P1, Structural and Optical Properties of (In,Ga)N/GaN Quantum Wells Grown by Plasma-Assisted Molecular Beam Epitaxy:** O. Brandt<sup>1</sup>; P. Waltereit<sup>1</sup>; S. Dhar<sup>1</sup>; U. Jahn<sup>1</sup>; Y. J. Sun<sup>1</sup>; A. Trampert<sup>1</sup>; K. H. Ploog<sup>1</sup>; <sup>1</sup>Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, Berlin 10111 Germany

We investigate the synthesis of (In,Ga)N/GaN multiple quantum wells by plasma-assisted molecular-beam epitaxy (MBE). For metal-stable growth, massive In surface segregation is revealed. The In depth profiles

obtained by secondary ion-mass spectrometry exhibit a top-hat In distribution and are thus indicative of a zeroth order segregation mechanism instead of a first order process as observed for other materials systems. As additionally evidenced by transmission electron microscopy, the segregation of In during metal-stable growth results in quantum wells with smooth interfaces but significantly larger width than intended. The resulting blue-shift of the transition energy may be the reason for the frequent conclusion that the theoretical polarization fields of Bernardini et al. [Phys. Rev. B 56, R10024 (1997)] are too large for (In,Ga)N. Being in possession of the (at least approximately) correct structural parameters, we find the theoretical fields to be in very satisfactory agreement with the those deduced from experimental data. For a thorough understanding of the spontaneous emission from these structures both electrostatic fields and compositional fluctuations have to be taken into account. Both the transition energies and radiative decay times in photoluminescence are shown to be in agreement with the quantum-confined Stark-effect in these structures. Using cathodoluminescence spectroscopy, we investigate the dependence of transition energy and quantum efficiency on both temperature and excitation density. At low temperatures, recombination is governed by localized states whereas for high temperatures extended states dominate. This finding is in agreement with the temperature dependence of the radiative decay time which is utilized as a probe of the dimensionality of the system. A quantitative analysis of these experiments via coupled rate equations shows that the localization depth in these MBE-grown (In,Ga)N/GaN quantum wells is around 20-30 meV. This shallow localization is found to significantly enhance the internal quantum efficiency up to a temperature of about 100K.

9:00 AM

**P2, Intersubband and Interband Optical Absorption Study of Strain-Compensated InGaAs-InGaP Superlattices Grown on GaAs:** Mykhaylo Semtsiv<sup>1</sup>; Oliver Bierwagen<sup>1</sup>; Ted W. Masselink<sup>1</sup>; Felix Eickemeyer<sup>2</sup>; <sup>1</sup>Humboldt-Universität zu Berlin, Dept. of Physics, Invalidenstrasse 110, Berlin 10115 Germany; <sup>2</sup>Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie, Dept. "C", Max-Born-Str. 11, Berlin D-12489 Germany

We study In<sub>0.32</sub>Ga<sub>0.68</sub>As-In<sub>0.32</sub>Ga<sub>0.68</sub>P strain-compensated superlattices grown on GaAs as an Al-free candidate material system for intersubband absorption and emission. In this presentation, we describe the growth of strain-compensated InGaP/InGaAs superlattices on GaAs and their subband structures by directly measuring the interband and intersubband absorption. These data are used to estimate the conduction band offset and the energetic limits for electronic intersubband transitions. Samples for this study were grown by gas-source MBE on semi-insulating GaAs substrates. The growth temperature of both the InGaP and InGaAs was 350°C to avoid 3D interface growth<sup>[1-3]</sup>. Thicknesses of the InGaP barriers and the InGaAs wells were chosen to simultaneously tune the intersubband energy separations and to achieve strain compensation (except the 10-nm well sample design, where full strain compensation is impossible because of InGaP critical thickness, being 15nm under mentioned growth conditions); we usually achieve an average lattice mismatch of the strain-compensated superlattice with respect to the substrate of better than 200 ppm. Sharp, dislocation-free interfaces are observed using TEM and confirmed through the number and narrowness of the satellite peaks in the X-ray diffraction spectra. The InGaP barriers are doped with Si to obtain sheet concentration of ~10<sup>12</sup> cm<sup>-2</sup> per well, so that the Fermi level is between the first and second subbands and the 1e-2e intersubband absorption is enabled. The electron concentration is confirmed by Hall measurements, C-V profiling, and photoluminescence line-shape analysis. The mid-infrared absorption spectra of two representative structures demonstrate sharp single peaks. Both structures have In<sub>0.32</sub>Ga<sub>0.68</sub>P barriers that are 10nm thick; the In<sub>0.32</sub>Ga<sub>0.68</sub>As wells of one structure are 10nm and of the other structure are 5.8nm. The measured peaks in absorption at 1150 and 1360 cm<sup>-1</sup>, corresponding to 143 and 169 meV, are attributed to the e1-to-e2 transition. These values are also consistent with the interband absorption data, when the estimated energy difference between the hh1 and hh2 states is included. This subband separation requires a conduction band offset of 440 to 700 meV; the large uncertainty reflects the uncertainty in the influence of the strain (both internal within the strain-compensated structures and total) and nonparabolicity of conduction subbands. Based on these data, we expect a maximum e1-e2 separation of about 250 meV. Replacing the InGaP with InAlGaP is expected, however, to allow still higher transition ener-



gies. <sup>1</sup>C. H. Yan and C. W. Tu, *J. Cryst. Growth* 164 (1996) 276; <sup>2</sup>J.-S. Liu, J.-S. Wang, K. Y. Hsieh, H.-H. Lin, *J. Cryst. Growth* 206 (1999) 15; <sup>3</sup>A. Ponchet, A. Le Corre, A. Godefroy, S. Salaun, A. Poudoulec, *J. Cryst. Growth* 153 (1995) 71.

#### 9:20 AM Student

**P3, Effects of Annealing on the Lateral Ordering of InAs/GaAs Quantum Dot Superlattices:** *Wenzhou Chen<sup>1</sup>; Byungha Shin<sup>1</sup>; Rachel S. Goldman<sup>1</sup> Adrienne Stiff<sup>2</sup>; Pallab K. Bhattacharya<sup>2</sup>; <sup>1</sup>University of Michigan, Matls. Sci. & Eng., 2300 Hayward St., Ann Arbor, MI 48109-2136 USA; <sup>2</sup>University of Michigan, Electl. Eng. & Compu. Sci., 1301 Beal Ave., Ann Arbor, MI 48109-2122 USA*

Self-assembled quantum dots have been shown to develop during epitaxial growth of highly mismatched films in the Stranski-Krastanow growth mode. After the initial growth of a few monolayers wetting layer, island nucleation results in the formation of self-assembled quantum dots. Stacks of capped quantum dots, or quantum dot superlattices, have the potential to form vertically and laterally ordered, three-dimensional dot lattices, which have unique electronic and optical properties. Although highly ordered dot arrays have been achieved in a number of materials systems, the limitations to the perfection of the dot lattices are not fully understood. In an earlier study of 1-, 5-, 10-, and 20-period InAs/GaAs quantum dot superlattices, we showed that as the number of the periods in the superlattice increased, the average spacing between vertically organized columns decreased<sup>1</sup>. In that case, the relative roles of bulk diffusion and strain-enhanced diffusion in determining the column spacing were not fully understood. Here, we have investigated the effects of annealing on the lateral ordering of a range of molecular beam epitaxially grown InAs/GaAs quantum dot superlattices, using ultra high vacuum cross-sectional scanning tunneling microscopy (XSTM). We have eliminated the role of differing residual strains by comparing superlattices with the same number of periods. For example, for a series of 5-period superlattices, we find that the linear density of vertically organized dot columns increases, and the average spacing between the dot columns decreases as a function of annealing time. Interestingly, the spacing between dot columns is constant throughout the thickness of a particular superlattice. The trend of decreasing dot column spacing as a function of annealing time is very similar to the earlier study mentioned above<sup>1</sup>. Together, these results suggest that bulk diffusion is the predominant factor in determining the ultimate column spacing in the quantum dot superlattice arrays. We will discuss these results, along with strategies for enhancing the ordering of the quantum dot superlattices by elimination of the wetting layer. This work was supported in part by the Army Research Office (MURI Program). <sup>1</sup>B. Lita, R. S. Goldman, J. Phillips, and P. K. Bhattacharya, *Appl. Phys. Lett.* 74, 19 (1999).

#### 9:40 AM

**P4, Growth and Characterization of IV-VI Semiconductor Multiple Quantum Well Structures:** *Patrick J. McCann<sup>1</sup>; Huizhen Wu<sup>1</sup>; Ning Dai<sup>2</sup>; <sup>1</sup>University of Oklahoma, Sch. of Electl. & Compu. Eng., 202 W. Boyd Ave., Rm. 219, Norman, OK 73019 USA; <sup>2</sup>University of Oklahoma, Dept. of Physics & Astron., Norman, OK 73019 USA*

Direct interband transitions in IV-VI materials occur at the L-points in the Brillouin zone. The constant energy surfaces for electrons (and holes) are defined as prolate ellipsoids of revolution with the major axis along the four equivalent  $\langle 111 \rangle$  directions. When IV-VI multiple quantum well (MQW) structures are grown on (111)-oriented substrates one L-valley is normal to the substrate surface, while the other three L-valleys are at oblique angles. Two different effective masses thus exist in the [111] direction of potential variation. The L<sup>N</sup>-valley (L-valley normal to the substrate surface) has heavier electrons (and holes) than the three-fold degenerate L<sup>O</sup>-valley (L-valleys oblique to the substrate surface). L-valley degeneracy is thus removed such that L<sup>N</sup>-valley transitions are at a lower energy than the three-fold degenerate L<sup>O</sup>-valley transitions. Experimental proof of L-valley degeneracy removal has recently been obtained with the molecular beam epitaxial (MBE) growth of PbSe/PbSrSe MQW structures on (111)-oriented BaF<sub>2</sub> substrates and their characterization by differential Fourier transform infrared (FTIR) transmission spectroscopy. Results showed an increase from 4 meV to 20 meV between ground state L<sup>N</sup>-valley and L<sup>O</sup>-valley transitions as the QW width decreases from 29.7nm to 9.7nm. Such separation is beneficial for laser fabrication because the approximate four-fold reduction in the density of the lowest excited states reduces the excitation threshold for population inversion. Recent experimental results including observation of room

temperature continuous wave photoluminescence from IV-VI MQW materials grown on (111)-oriented BaF<sub>2</sub> and silicon substrates as well as a six-fold reduction in lasing threshold when a MQW active region is included in a IV-VI vertical cavity surface emitting laser (VCSEL) show the utility of this phenomenon. Presented here are new results on the growth and characterization of parabolic IV-VI MQW structures. Samples were grown by MBE on BaF<sub>2</sub>(111) substrates and characterized by differential FTIR transmission spectroscopy. Well widths varied from 40nm to 100nm. Unwanted Fabry-Perot interference fringes in the transmission spectra were effectively eliminated by coating the top surface of the MQW samples with an antireflection film. This enabled unambiguous observation of L<sup>N</sup>-valley and L<sup>O</sup>-valley transitions as well as up to six principle quantized electron and hole sub-band transitions. Analysis of the results shows that the quantum size effect, as opposed to epitaxial layer strain, is primarily responsible for the splitting of L-valley degeneracy. In addition, intervalley splitting energies and the spacings of the principle energy levels allowed determination of the deformation potential constants for PbSe, and the high-quantized transition energies allowed determination of the nonparabolicity parameters for the conduction and valence bands of PbSe. These parameters will be useful for design of future devices based upon IV-VI materials.

#### 10:00 AM Break

## Session Q: Quantum Dot Devices

Thursday AM Room: UCEN Harbor  
June 27, 2002 Location: University of California

*Session Chairs:* Glenn Solomon, Stanford University, 76 S. Ginzton Lab., Stanford, CA 94305-4075 USA;  
Ben Shanabrook, Naval Research Laboratories, Nanostructures Section, Code 6870, Washington, DC 20375-5000 USA

#### 10:20 AM Invited

**Q1, InAs Quantum Dot Infrared Photodetectors:** *Joe C. Campbell<sup>1</sup>; Anupam Madhukar<sup>2</sup>; <sup>1</sup>University of Texas at Austin, Microelect. Rsrch. Ctr., Austin, TX 78712 USA; <sup>2</sup>University of Southern California, Dept. of Matls. Sci. & Physics, Los Angeles, CA 90089 USA*

As a potential candidate for mid-infrared (3~5 mm) and far-infrared (8~14 mm) photon detection, the quantum dot infrared photodetector (QDIP) has been the subject of extensive research efforts in recent years. Normal-incidence QDIPs with n-n-n and n-i-n vertical configurations have been reported. Compared with quantum well infrared photodetectors (QWIPs), QDIPs are sensitive to normal-incidence infrared radiation owing to three-dimensional confinement of the electrons in the quantum dots, a characteristic that is advantageous for focal plane arrays. In addition, due to greatly suppressed electron-phonon scattering, QDIPs have the advantages of low dark current and long carrier lifetimes, which establish the potential for high temperature operation. Furthermore, photoconductive gain that ranges from unity to several thousand has been reported. Normal-incidence QDIPs with encouraging performance at ~77K have been demonstrated from 3mm to 14mm wavelength. In the mid-wavelength infrared (MWIR) regime, we demonstrated a peak detectivity (D\*) of 1.5\*10<sup>9</sup> cmHz<sup>1/2</sup>/W at 7.2mm at 77K in Al-free GaAs(001)/InAs n-i-n QDIPs. To improve upon the dark current and D\*, we introduced the notion of a current blocking AlGaAs layer in the otherwise GaAs confinement layers. With such an AlGaAs current blocking layer, a peak D\* at 3.7mm of 3\*10<sup>9</sup> cmHz<sup>1/2</sup>/W at 100K in n-n-n and a peak D\* at 6.2mm of 10<sup>10</sup> cmHz<sup>1/2</sup>/W at 77K in n-i-n have been achieved in GaAs(001)/InAs QD based QDIPs. In the long-wavelength infrared regime (LWIR), a QDIP based on GaAs(001)/InGaAs QDs in n-n-n structure with a peak D\* at 13mm of 2\*10<sup>8</sup> cmHz<sup>1/2</sup>/W at 78K has been demonstrated. Recently, we have demonstrated the first normal-incidence bias-controlled tunable mid (~5.6 mm) and long (~10 mm) wavelength infrared (IR) photoresponse in a QDIP structure. This n-i-n structure is based on InGaAs capped GaAs(001)/InAs quantum dots (QDs) with two different quantum dot size distributions. Its 77K peak detectivities at mid (~5.6 mm) and long (~10 mm) wavelength are 5.8\*10<sup>9</sup> cmHz<sup>1/2</sup>/W and 7.3\*10<sup>8</sup> cmHz<sup>1/2</sup>/W, respectively. In the long-wavelength infrared regime



( $\lambda > 8$  nm) all reported normal-incidence peak detectivities of QDIPs (with contacts in the vertical configuration), to date, are below  $10^9$  cmHz<sup>1/2</sup>/W at  $\sim 77$ K. Recently, we have realized a narrow, essentially unimodal, QDIP intraband photoresponse at 8-9nm with a similar structure based on In<sub>0.15</sub>Ga<sub>0.85</sub>As capped GaAs(001)/InAs QDs having an essentially unimodal QD size distribution. These devices have achieved low dark current, low noise, and high detectivity at 8-9nm and 77K. Figure 1 shows a schematic of the QDIP structure and the band diagram under negative bias is shown schematically in Figure 2. The absolute spectral responsivity was calibrated with a blackbody source (T = 995K). Figure 3 shows the peak responsivity versus bias at temperatures of 77K, 100K, and 120K. At 77K, with increase in positive bias, the responsivity increased from 13 mA/W at 0.2 V to 660 mA/W at 0.9 V. For negative bias, the responsivity increased from 22 mA/W at -0.2 V to 600 mA/W at -0.9 V. The different responsivity curves for the positive and negative bias are due to the asymmetric band structure. Figure 12 shows the peak detectivity at 77K and 100K. The best performance was achieved at 77K and -0.2 V where the peak detectivity was  $3.2 \cdot 10^9$  cmHz<sup>1/2</sup>/W. The corresponding responsivity was 22 mA/W. Note the rapid decrease of the detectivity with increase in temperature for both peaks.

#### 11:00 AM Student

**Q2, Low-Threshold InP Quantum-Dot Lasers Coupled to Strained InGaP Quantum Wells Grown by Metalorganic Chemical Vapor Deposition:** Richard D. Heller<sup>1</sup>; Jae-Hyun Ryou<sup>2</sup>; Russell D. Dupuis<sup>1</sup>; Gabriel Walter<sup>3</sup>; Nick Holonyak<sup>4</sup>; Chavva V. Reddy<sup>4</sup>; Venkatesh Narayanamurti<sup>4</sup>; David T. Mathes<sup>5</sup>; Robert Hull<sup>3</sup>; <sup>1</sup>University of Texas at Austin, Electl. & Compu. Eng., Microelect. Rsrch. Ctr., Austin, TX 78712 USA; <sup>2</sup>Honeywell, VCSEL Products Div., Plymouth, MN 55441 USA; <sup>3</sup>The University of Illinois at Urbana-Champaign, Ctr. for Compound Semiconductor Microelect., 208 N. Wright St., Urbana, IL 61801 USA; <sup>4</sup>Harvard University, Gordon McKay Lab. of Appl. Sci., Pierce 271A, Cambridge, MA 02138 USA; <sup>5</sup>The University of Virginia, Dept. of Matls. Sci. & Eng., Thornton Hall, Charlottesville, VA 22903 USA

InP self-assembled quantum-dot (SAQD) structures offer the ability to realize injection lasers operating in the visible wavelength region with improved performance characteristics such as a low threshold current density and high characteristic temperature. InP quantum-dots (QDs) have been grown and characterized on direct-bandgap In<sub>0.49</sub>Ga<sub>0.51</sub>P matrices by several research groups and on direct/indirect In<sub>0.49</sub>(Al<sub>x</sub>Ga<sub>1-x</sub>)<sub>0.51</sub>P matrices (x=0.0, 0.3, 0.6, and 1.0) by these authors. We have studied the optical properties of the quantum dots grown on various matrices and explored the coupling of the QDs to a nearby quantum well to improve the carrier transport and kinetics in the quantum dots. We describe the effects of coupling of the InP QD states to the electronic states of InGaP quantum wells grown below and above the quantum dots, resulting in the coupling of the quantum dots through electronic states in the quantum wells. The InP QD + QW growth studies are performed by altering growth temperatures and times and using various In<sub>0.49</sub>(Al<sub>x</sub>Ga<sub>1-x</sub>)<sub>0.51</sub>P matrices and various InGaP QW layers. The morphology changes of the exposed SAQDs depend on the growth time and the matrix material, and are characterized by AFM. Photoluminescence spectra were taken at 4K and 300K to determine the light-emitting characteristics of the In<sub>0.49</sub>(Al<sub>x</sub>Ga<sub>1-x</sub>)<sub>0.51</sub>P/InP quantum-dot heterostructures; PL spectra from these structures exhibit emission in the visible orange and red spectral regions. Also, TEM is used to characterize the microscopic material quality and morphology of the individual QD and the interfaces between SAQDs and the cladding layers. These InP QD active regions have been incorporated into various laser separate-confinement active regions, and we report optically pumped 300K pulsed and CW lasing from InP SAQDs in the visible wavelength range. We also have demonstrated low-threshold (J<sub>th</sub>  $\sim 1.4$  KA/cm<sup>2</sup>) electrically pumped InP QD diode lasers. Additionally, optically and electrically pumped 300K lasers have been obtained using this unique active region design; these lasers show improved operation compared to the lasers having QD-based active regions with threshold current densities as low as J<sub>th</sub>  $\sim 0.4$  KA/cm<sup>2</sup>. Further, we have incorporated both tensile- and compressive-strained InGaP QWs to optimize the uniformity and density of the QDs. Using this approach, we have improved the QD density from  $1 \times 10^{10}$  cm<sup>-2</sup> to as much as  $2-3 \times 10^{10}$  cm<sup>-2</sup>. We will describe the growth and properties of these novel QD/QW injection lasers as well as compare to QD lasers.

#### 11:20 AM Student

**Q3, 1.3-Micron InAs Quantum Dot Laser with T<sub>0</sub>=213K from 0 to 80°C:** Oleg B. Shchekin<sup>1</sup>; Dennis G. Deppe<sup>1</sup>; <sup>1</sup>The University of Texas at

Austin, Electl. & Compu. Eng., Austin, TX 78758 USA

GaAs-based lasers can now be made to operate at 1.3-micron using InAs or InGaAs quantum dots (QDs), and may offer a low cost alternative to InP-based quantum well lasers. QD lasers have already been demonstrated to be capable of very low threshold current and current density, but their T<sub>0</sub>'s reported to date are not much higher than that of InP-based lasers. Also, the QD lasers have been unable to demonstrate the proposed high modulation bandwidths, and are inferior to planar quantum well lasers in their modulation response. In this paper, we provide evidence that p-type doping of QD active region dramatically enhances the performance of QD lasers. We first use a quasi-equilibrium model to show that built-in holes dramatically increase gain and differential gain of QD active regions at low injection levels. The p-doping counters gain lowering due to thermal redistribution of holes between closely spaced QD hole levels. As a consequence of increased gain we expect p-doped QD lasers to have higher characteristic temperatures and lower thresholds for shorter device cavity lengths. We also model the modulation response of QD lasers and show that the increase in differential gain is expected to significantly improve laser modulation response. We then fabricate QD edge emitting lasers operating at 1.3 micron with various amounts of p-type modulation doping of the active region. These devices are compared side by side to undoped devices. The gain enhancement due to p-doping is evident when threshold current densities are compared at short cavity lengths. For undoped two-stack QD lasers, ground state operation is obtained with cavity lengths down to  $\sim 1.6$  mm, while similar devices doped with either 26 or 52 acceptors per QD operate on the ground state even for cavity lengths of 0.9 mm. The characteristic temperatures are then measured on as-cleaved wide area devices under pulsed operation with cavity lengths between 2.8-3.8mm. For an undoped device, the T<sub>0</sub> is 85K between 0 and 80°C, but for devices with 26 and 52 acceptors per QD it increases to 145K and 161K respectively. We have also fabricated ridge-waveguide QD edge emitting lasers with three QD stacks doped with 26 acceptors per dot, cavity length of 700 micron and ridge aperture width of 5 micron. Four reflective pairs of ZnSe/MgF were deposited on the back facet and one pair on the front. For these devices, the T<sub>0</sub> measured between 0 and 80°C is 213K in pulsed operation and 196K in CW. This is the highest value of T<sub>0</sub> yet reported for a QD laser in this temperature range. The threshold current at 26°C is 4.4 mA with peak power  $\sim 15$  mW, and at 80°C the threshold current is at 6.4 mA and peak power  $\sim 11$  mW.

#### 11:40 AM

**Q4, Evaluation of Performance Limitations in Quantum Dot Infrared Detectors:** Jamie D. Phillips<sup>1</sup>; <sup>1</sup>The University of Michigan, Dept. of Electl. Eng. & Compu. Sci., 1301 Beal Ave., Ann Arbor, MI 48109 USA

Self-assembled nanostructures have demonstrated the ability to provide arrays of quantum dots (QD) capable of absorbing and emitting light through optical processes between quantum-confined electronic states. Detectors based on intraband optical absorption permits detection corresponding to energies much smaller than the bandgap of the material. This bypasses the need to use low bandgap materials, in particular HgCdTe, which is difficult and costly to grow and process. Due to the high potential payoff, there is a large interest in finding a suitable alternative technology to HgCdTe- the current infrared detector performance leader. Intraband optical absorption in self-assembled QDs has been applied to a device: the quantum dot infrared photodetector (QDIP). QDIPs have been predicted to outperform their quantum well (QWIP) predecessors due to their intrinsic sensitivity to normal incidence excitation and reduced phonon scattering rates. Several groups have demonstrated successful QDIP operation, but results have not rivaled QWIP performance nor come close to HgCdTe detector performance. In general, there has not been sufficient analysis of QDIPs to determine why performance is lacking and whether they have the potential to rival other detector technologies. In this work, the operation of QDIPs is modeled to provide insight to the fundamental detector performance limitations based on thermal generation and recombination mechanisms. The analysis determines limiting factors in an infrared material of interest that is independent of device configuration, permitting comparison between differing materials technologies. Limitations on QDIPs are then compared to QWIPs and HgCdTe. The analysis helps to explain the reduced performance of QDIPs, where inhomogeneous broadening and non-optimal bandstructure are the primary suspected limiters. QDIPs are predicted to outperform QWIPs by more than an order of magnitude for the case of an optimized

electronic structure and an inhomogeneous broadening in the QD ensemble similar to present-day results. Under the assumption of a more ideal QD ensemble, QDIPs are expected to have performance competitive to the theoretical performance of HgCdTe.

## Session R: Epitaxy: Metamorphic/Strain

Thursday AM      Room: UCEN Lobero  
June 27, 2002      Location: University of California

*Session Chair:* Eugene A. Fitzgerald, Massachusetts Institute of Technology, Dept. of Matl. Sci. & Eng., 77 Massachusetts Ave., Rm. 13-4053, Cambridge, MA 02139 USA

### 8:20 AM Student

**R1, Evolution of Surface Morphology and Stress Relaxation in  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaAs}$ :** Benny Perez-Rodriguez<sup>1</sup>; G. K.M. Martin<sup>1</sup>; J. Mirecki Millunchick<sup>1</sup>; <sup>1</sup>University of Michigan, Matls. Sci. & Eng., Ann Arbor, MI 48109 USA

The mechanism for stress relaxation has been investigated during growth of InGaAs/GaAs(100) heterostructures in a regime where misfit dislocations and surface morphology strongly interact. Real time stress evolution was obtained using an in situ Multi-Beam Optical Stress Sensor (MOSS) measurement during Molecular Beam Epitaxy of  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$  on a semi-insulating GaAs substrate misoriented 2° toward the (110) planes. This real time data has been combined with detailed analysis of X-Ray Diffraction and Atomic Force Microscopy. Several distinct stages of the stress evolution were observed during growth that are correlated to the development of morphology and strain relaxation in these films. Figure 1(a) shows the stress-thickness vs deposited thickness obtained using MOSS, and figure 1(b) shows the corresponding strain relieved percentage vs deposited thickness. The stress-thickness curve undergoes a linear increase for approximately 250Å. For 250Å<900Å, the slope of the stress-thickness curve decreases slightly, indicating some relaxation in the film. For 900Å<400Å, the measured stress-thickness curve exhibits a negative slope transition. Subsequent to the negative slope transition regime, the stress-thickness evolves with a positive constant slope. Assuming that the growth rate is constant in time, the data may be converted from the stress-thickness versus thickness to strain-relieved versus thickness. The stress evolution is divided in four regimes: pseudomorphic growth, slow strain relaxation, fast strain relaxation and saturation. The strain-relieved percentage curve shows that for  $hf < 250\text{Å}$ , essentially no strain is relieved. This is the pseudomorphic growth regime. Relatively slow strain relaxation occurs for  $250\text{Å} < hf < 900\text{Å}$ , during which less than 19% of the strain is relieved. Fast relaxation occurs for  $900\text{Å} < hf < 1400\text{Å}$  and by  $hf = 1200\text{Å}$ , 50% of the film strain has been relaxed. Beyond 1400Å, the rate of strain relief continues to decay for the duration of the growth. Figure 2(a) shows the AFM image for a 100Å thick film, non-planar surface morphology starts to develop early in the pseudomorphic regime. As the films thicken, large 3D structures develop resulting in an increase in the RMS roughness, thus partially relieving strain. As the growth thickness continues beyond 900Å, a cross-hatch morphology characteristic of misfit dislocation formation appears, thus rapidly relaxing strain. Simultaneously, the 3D structures begin to disappear, and the RMS roughness decreases. Beyond 1400Å, the film continues to relax slowly and the cross-hatch pattern fades. From these data, we conclude that stress relaxation for this system begins prior to misfit dislocation formation via surface roughening. Once dislocations are introduced, strain relaxation proceeds rapidly. Because the driving force for roughening is reduced, the surface morphology flattens as the film becomes thicker.

### 8:40 AM Student

**R2, Growth of Compositionally-Graded InAlAs and InAsP Buffer Layers on InP Substrates Using Solid Source Molecular Beam Epitaxy:** Yong Lin<sup>1</sup>; Mantu K. Hudait<sup>1</sup>; David M. Wilt<sup>2</sup>; Steven A. Ringel<sup>1</sup>; <sup>1</sup>Ohio State University, Dept. of Electl. Eng., 205 Dreese Lab., Columbus, OH 43210 USA; <sup>2</sup>NASA Glenn Research Ctr., Photovoltaics & Space Environ. Branch, Cleveland, OH 44135 USA

Growth of low bandgap (< 0.74 eV) InGaAs on InP substrates is of interest for applications ranging from high-speed electronics, where metamorphic HEMT structures can exploit favorable band offsets to achieve high mobilities, to optoelectronics where sensitivity down to 2.5 μm is desired. Achieving these bandgaps requires the In content of InGaAs to be higher than the 53% lattice matched composition used for typical InGaAs/InP technology. The increased lattice constant of such layers generates compressive strain and, depending on thickness, strain relaxation via dislocation generation. To lower dislocation density, compositionally-graded buffer layers are of interest. Several alloy systems can span the lattice constant range from InP to that desired for the low bandgap InGaAs overlayers; InGaAs, InAlAs and InAsP. Here we use solid source molecular beam epitaxy to investigate the growth and structural properties of step graded InAlAs and InAsP grown on InP substrates, out to a total mismatch of ~1.5%. The focus is on comparing the impact of changing composition on the group V sublattice versus the group III sublattice to achieve lattice constant grading and efficient relaxation. InAlAs layers were grown with a starting, lattice-matched composition of  $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  and subsequently graded to higher In content (larger lattice constant) at an average rate of 10% In/μm. InAsP layers were grown with an average grading rate of 20% As/μm. Final compositions of  $\text{In}_{0.68}\text{Al}_{0.32}\text{As}$  and  $\text{InAs}_{0.32}\text{P}_{0.68}$  were chosen, each representing a misfit of 1.5% with respect to the InP substrate. These graded layers were grown at a temperature of ~ 520°C (for InAlAs) and ~ 485°C (for InAsP). Growth was monitored by reflection high-energy electron diffraction (RHEED). The initial (2x4) symmetry of the InP(001) surface observed by RHEED became blurry, but still observable, as a function of InAlAs growth time, which was minimized by reducing the exposure of the InP surface to an As flux prior to InAlAs growth. However, for InAsP growth which is initiated under a P flux, a strong (2x4) RHEED pattern was consistently observed, indicating the problem of As replacing P in the InP surface under As exposure during InAlAs nucleation. A comparison of growth on vicinal (2° off-cut (001) towards <110>) and (001) substrates revealed similar results. The RHEED results were consistent with ex-situ properties, where well-defined, two dimensional cross-hatch morphology was observed for all InAsP buffers, while InAlAs displayed a more random surface morphology consisting of background roughness overlaying a crosshatch that at times was more pronounced in one direction. Triple axis x-ray diffraction revealed that all buffers achieved similar relaxation, but with significantly more lattice tilt for the InAlAs. A comparison between these approaches, including TEM studies to observe differences in dislocation structure and scanning probe microscopy to correlate surface features, will be presented.

### 9:00 AM Student

**R3, Growth and Polishing of InAlAs Graded Buffer Layers for InAs-Based Device Structures:** A. M. Noori<sup>1</sup>; R. S. Sandhu<sup>1</sup>; S. L. Hayashi<sup>1</sup>; M. Wojtowicz<sup>2</sup>; A. Cavus<sup>2</sup>; T. R. Block<sup>2</sup>; M. S. Goorsky<sup>1</sup>; <sup>1</sup>University of California, Dept. of Matls. Sci. & Eng., Los Angeles, CA 90095 USA; <sup>2</sup>TRW, Elect. Tech. Div., Space & Elect. Grp., Redondo Beach, CA 90278 USA

Virtual substrates for large lattice parameter structures with semi-insulating bulk properties can be produced through the graded buffer layer formation of  $\text{In}_x\text{Al}_{1-x}\text{As}$  layers. We demonstrate that—through graded buffer growth and chemical-mechanical polishing—structures can be created with fully relaxed template layers with surface r.m.s roughness of about 0.2nm. The composition of the InAlAs film is initially lattice-matched to the semi-insulating InP substrate and graded to InAs during molecular beam epitaxial growth. The grading rate and growth temperatures were changed to determine the growth conditions that produced the highest degree of relaxation, as determined through x-ray reciprocal space mapping. The growth conditions that produced the most complete relaxation (relatively low grading rate with a buffer layer thickness of » 1.6mm and higher growth temperature) also possessed the highest surface roughness (18.3 nm; using atomic force microscopy) whereas structures grown using higher grading rate or lower grading temperature produced smoother surfaces (» 9 nm) but did not exhibit complete relaxation. Plan view and cross-section transmission electron microscopy images confirm a high density of interfacial misfit dislocations and a misfit dislocation-free region of about 200nm near the buffer layer surface. To reduce the surface roughness of the completely relaxed structures, chemical mechanical polishing was used. Dilute NaOCl, NaOCl solutions with 70nm  $\text{Al}_2\text{O}_3$  abrasive (Chemlox), citric acid solutions, and D.I. water were all employed as polishing solutions using an automated polishing

tool and varying pad force, rotation rates, and polishing time. The lowest surface roughness (0.2 nm) was achieved using dilute NaOCl solutions with high uniformity over 3" wafers. Comparison measurements on separate InAs substrates confirm that little polishing damage is introduced using these polishing parameters. Reciprocal space mapping of the polished structures indicated that less than 30nm of the top of the graded buffer layer is removed during the polishing sequence. These virtual substrates are used for subsequent epitaxial deposition of device structures.

#### 9:20 AM Student

**R4, Influence of Growth Parameters on Antimony Incorporation During Molecular Beam Epitaxy of III-Arsenide-Antimonides:** *Rubin Sidhu*<sup>1</sup>; Xiaoguang Sun<sup>1</sup>; Archie L. Holmes<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Electl. & Compu. Eng., Austin, TX 78712 USA

Group III-Arsenide-Antimonides are interesting III-V alloys, and hold much promise for heterojunction transistors and mid-IR communication devices. On GaAs substrates, GaAs<sub>1-y</sub>Sb<sub>y</sub> has been shown to emit at 1.3μm using strained quantum wells. On InP substrates, lattice matched Al<sub>1-x</sub>Ga<sub>x</sub>As<sub>1-y</sub>Sb<sub>y</sub>/GaAs<sub>1-y</sub>Sb<sub>y</sub> provide high refractive index step materials for DBR mirrors, offering a much needed improvement over Ga<sub>x</sub>In<sub>1-x</sub>As<sub>1-y</sub>P<sub>y</sub>/InP. Control over the group-V incorporation in the MBE growth of mixed group-V alloys such as Al<sub>1-x</sub>Ga<sub>x</sub>As<sub>1-y</sub>Sb<sub>y</sub> is a lot more challenging than the control of group-III composition. This is because an over flux of group-V species forces competition between group-V atoms for a limited number of anion sites, as compared to a near unity sticking coefficient of the group-III species. Antimony incorporation in III-AsSb is strongly dependent on the various growth parameters, namely, substrate temperature, group III growth rates, and Arsenic and Antimony beam equivalent pressures (BEPs). This dependence was studied by growing GaAs<sub>1-y</sub>Sb<sub>y</sub> as strained QWs on GaAs, and AlAs<sub>1-y</sub>Sb<sub>y</sub> bulk layers on InP, using solid source MBE. Antimony incorporation in the films was determined using room temperature photoluminescence and x-ray diffraction. We observed that the 300K photo luminescence peaks shift towards shorter wavelengths with increasing growth temperature of GaAs<sub>1-y</sub>Sb<sub>y</sub> on GaAs, indicating decreasing Antimony incorporation in the films. We believe this is due to increased Sb desorption from the growth surface at higher temperatures. Antimony incorporation was also seen to be a strong function of Ga growth rate, increasing with the Ga growth rate until about 0.6 mono-layers/second and then leveling out. This suggests that at higher Ga growth rates, there are more Ga atoms available for Sb adatoms to bond with, which keeps the Sb atoms from desorbing from the surface. The same trend was observed in AlAs<sub>1-y</sub>Sb<sub>y</sub> growth on InP. While growing AlAs<sub>1-y</sub>Sb<sub>y</sub> on InP, Arsenic seemed to incorporate preferentially over Antimony. At a high Arsenic BEP of 6.0x10<sup>-6</sup> torr, a change in Sb BEP produced little change in Sb incorporation in the film, whereas, at a lower As BEP of 3.0x10<sup>-6</sup> torr, a similar change in Sb BEP produced a larger change in Sb incorporation. The same is also evident from the observation that increasing the As BEP while keeping the As/Sb BEP ratio fixed at 1.0 resulted in a decreased Sb incorporation. Good lattice match of AlAs<sub>0.55</sub>Sb<sub>0.45</sub> on InP was observed at both As and Sb BEPs of 3.0x10<sup>-6</sup> torr for a high Al growth rate.

#### 9:40 AM

**R5, Micro-X-Ray Fluorescence and Micro-Photoluminescence in Quaternary Layers Obtained by Selective Area Growth:** *Andrei Sirenko*<sup>1</sup>; C. L. Reynolds<sup>1</sup>; L. J. Peticolas<sup>1</sup>; A. Ougazzaden<sup>1</sup>; A. Kazimirov<sup>2</sup>; R. Huang<sup>2</sup>; E. Fontes<sup>2</sup>; D. Bilderback<sup>2</sup>; <sup>1</sup>Agere Systems, Optoelect. Rsrch., 9999 Hamilton Blvd., Breinigsville, PA 18031 USA; <sup>2</sup>Cornell University, CHESS, 277 Wilson Lab., Ithaca, NY 14853 USA

Properties of the Selective Area Grown (SAG) ternary and quaternary layers of InGaAs and InGaAsP with the thickness between 0.05 and 0.4 μm produced by MOVPE have been investigated using a combination of micro photoluminescence (laser spot size of 5 μm) and micro-beam x-ray fluorescence (spot size of 1 μm) excited with a synchrotron radiation at the D1 beamline of the Cornell High Energy Synchrotron Source. A big variety of the mask geometries for Selective Area Growth including ultra-wide masks, greed masks, and masks with ultra-narrow openings have been investigated with this new technique. In both, ternary and quaternary layers, we observed a significant variation of the III-element composition with increase of the mask width and decrease of the opening between masks. In contrast, concentration of the V-elements in quaternary layers did not show any significant change within accuracy of our measurement. Effects of the SAG growth on the compositional and thick-

ness variation in the investigated systems become more pronounced with increase of the growth pressure.

#### 10:00 AM Break

## Session S: Epitaxy: Doping and Defects

Thursday AM  
June 27, 2002

Room: UCEN Lobero  
Location: University of California

*Session Chair:* Jeff G. Cederberg, Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185-0601 USA

#### 10:20 AM Student

**S1, Tellurium-Induced Disorder of Cu-Pt Type Ordered Structures in In<sub>0.5</sub>(Al<sub>1-x</sub>Ga<sub>x</sub>)<sub>0.5</sub>P Layers:** *Kuo-Lih Chang*<sup>1</sup>; K. C. Hsieh<sup>1</sup>; P. N. Grillo<sup>2</sup>; R. D. Pai<sup>2</sup>; J.-W. Huang<sup>2</sup>; G. E. Hofler<sup>3</sup>; <sup>1</sup>University of Illinois at Urbana-Champaign, Electl. & Compu. Eng., 208 N. Wright St., #150, Urbana, IL 61821 USA; <sup>2</sup>LumiLeds Lighting, US LLC, R&D, 370 W. Trimble Rd., San Jose, CA 95131 USA; <sup>3</sup>Agilent Technologies, R&D, 3500 Deer Creek Rd., Palo Alto, CA 94888 USA

Impurity-induced disordering can take place in intentionally-grown superlattice structures as well as in other atomic-scale ordered structures, such as Cu-Pt type ordering, which may spontaneously appear during epitaxial growth. The superlattice-like properties of Cu-Pt ordering result in Brillouin zone folding of the band structure, which reduces the bandgap of In(AlGa)P by approximately 90 meV. Such bandgap variations are in general undesirable in high volume laser diode or light emitting diode (LED) manufacturing since they introduce additional uncontrolled process variation. In this work, disordering of Cu-Pt ordering is studied with transmission electron microscopy and secondary ion mass spectroscopy (SIMS) in p-type (Mg-doped), n-type (Te-doped) and nominally undoped InAlP and In(AlGa)P layers. There are three sets of samples grown by MOCVD on Te-doped GaAs substrate for LED application. These samples consist of an n-type InAlP confining layer ~1μm, a nominally undoped active region including eight quantum wells and seven barrier layers, followed by p-type In(AlGa)P and InAlP layers (total ~1.5μm). Following the MOCVD growth step, a 50 μm thick GaP cap layer was grown on these structures via VPE for light extraction and current spreading in these LEDs. The first set of samples is used for studying VPE growth effect. Before VPE growth, Cu-Pt type ordering structures was observed in the upper half of the multiple quantum wells (MQW) and the p-type In(AlGa)P and InAlP layers above the MQW region. After VPE growth, all of the ordered structures are removed through this process. From the second set of samples, which were not doped with Mg in upper confining region, it still has the Cu-Pt ordered structures in MQW and upper In(AlGa)P and InAlP cladding layers before VPE growth. After VPE growth, Cu-Pt ordering is not observed in the MQW and upper In(AlGa)P regions. However, the top cladding InAlP layer still exhibits the ordered structures after VPE process. This result shows Mg diffusion may play an important role in removing Cu-Pt ordering from InAlP, but that Mg diffusion is not required to remove Cu-Pt ordering from the MQW and the In(AlGa)P cladding layer above it. The third set of samples is used to evaluate the effect of Te concentration on the Cu-Pt ordering phenomena. With a lower Te concentration (one order of magnitude), the Cu-Pt type ordering is present in the entire ~1μm n-type InAlP layer. After VPE growth, the Cu-Pt type ordering in all regions was removed. On the other hand, SIMS data demonstrates that no significant Te diffusion occurs during VPE annealing. This suggests that group III self diffusion must be responsible for removing Cu-Pt ordering in these samples. The high electron concentration in n-type material results in large amount of group III vacancies and enhances the group III self diffusion.

#### 10:40 AM Student

**S2, Minority Carrier Lifetime Studies in Heavily Beryllium-Doped P-Type GaAs:** *Thomas D. Boone*<sup>1</sup>; Jerry M. Woodall<sup>2</sup>; <sup>1</sup>Yale University, Electl. Eng., PO Box 208284, New Haven, CT 06520-8284 USA; <sup>2</sup>Yale University, Electl. & Compu. Eng., New Haven, CT 06520-8284 USA

The minority carrier recombination lifetime  $\tau$  is one of the more critical material parameters for increasing the modulation bandwidth of high-speed GaAs light emitting diodes (LEDs) for optical communication applications. This is due to the LED modulation bandwidth being inversely proportional to  $\tau$ . Increasing the doping density in the semiconductor reduces the lifetime inversely, resulting in higher LED modulation bandwidths. However, as doping continues to be increased non-radiative recombination mechanisms, such as Auger recombination, begin to dominate the recombination process. This has a deleterious effect on LED luminescence efficiency. The minority carrier lifetime as a function of p-type doping in liquid phase epitaxy (LPE) grown GaAs was characterized by Nelson and Sobers for doping levels between  $NA=1E15$  to  $NA=1E19$ . Within this doping regime the dominant recombination mechanism is direct band to band radiative recombination. With molecular beam epitaxy (MBE) doping levels have been achieved in excess of  $NA=1E20$ . By carefully controlling the MBE growth parameters we have achieved a minority carrier lifetime of approximately 100 ps for GaAs doped above  $NA=5E19$ . This lifetime is significantly longer than values recently reported for C doped GaAs. To the best of our knowledge our results represent the longest minority carrier lifetime reported for GaAs doped to  $NA>5E19$ . Analysis relating the lifetime to radiative and non-radiative recombination processes is included as well as results from time-resolved photoluminescence measurements, excitation photoluminescence measurements, and electrochemical capacitance voltage dopant profiling.

**11:00 AM**

**S3, Acceptor Doping Properties in  $(Al_xGa_{1-x})_{0.5}In_{0.5}P$  and AlGaInN: P.** N. Grillo<sup>1</sup>; R. D. Pai<sup>1</sup>; J.-W. Huang<sup>1</sup>; M. Misra<sup>1</sup>; S. A. Stockman<sup>1</sup>; <sup>1</sup>LumiLeds Lighting, US LLC, 370 W. Trimble Rd., San Jose, CA 95131 USA

Wide bandgap semiconductors such as AlGaInP and AlGaInN are of great interest for applications such as light emitting diodes, laser diodes, and transistors. Such wide bandgap semiconductors are plagued with difficulties in achieving acceptable p-type conductivity, however, due to inefficient acceptor incorporation, poor acceptor activation, and rapid acceptor diffusion. To gain a better understanding of these limitations on p-type doping, we have studied the effect of acceptor concentration, donor concentration, and alloy composition (or bandgap) on acceptor incorporation and diffusion in  $(Al_xGa_{1-x})_{0.5}In_{0.5}P$  and to a lesser extent in AlGaInN. Both metal organic chemical vapor deposition (MOCVD) and gas source molecular beam epitaxy (GSMBE) were used to grow the  $(Al_xGa_{1-x})_{0.5}In_{0.5}P$  samples, while the AlGaInN samples were all grown by MOCVD. All MOCVD grown samples were doped with Mg using  $Cp_2Mg$  while the GSMBE samples were doped by using a solid Be source. Although it is widely understood that acceptor incorporation decreases with increasing bandgap, this relationship between bandgap and acceptor incorporation has, to our knowledge, not been quantified. Our research of acceptor doping properties in  $(Al_xGa_{1-x})_{0.5}In_{0.5}P$  reveals a linear relationship between acceptor incorporation and alloy composition (or valence band energy) for both Mg and Be in  $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ . Moreover, we have observed a similar relationship between acceptor incorporation and Al composition in AlGaIn alloys. The observation of similar trends for two different alloy systems (AlGaInP and AlGaInN), two different growth techniques (MOCVD and GSMBE) and two different dopant species (gas source Mg and solid source Be), suggests that this linear relationship between Al content and acceptor incorporation may represent a fundamental phenomenon in Al-bearing semiconductors. We will also discuss the effect of donor species on acceptor incorporation and diffusion, and we will show that donor species enhance acceptor incorporation and suppress acceptor diffusion in  $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ . Evidence will be presented which indicates that this acceptor incorporation enhancement is governed by the tendency of the crystal to maintain a constant Fermi level at the crystal surface during growth. A simple model of dopant incorporation and diffusion will be presented to help explain these observations.

**11:20 AM Student**

**S4, Fast Photoconductive Materials Pumped at 1.55 $\mu$ m: ErAs:InGaAs:** Daniel C. Driscoll<sup>1</sup>; Micah P. Hanson<sup>1</sup>; Elisabeth Muller<sup>2</sup>; Elliott R. Brown<sup>3</sup>; Arthur C. Gossard<sup>1</sup>; <sup>1</sup>University of California, Mats. Dept., Santa Barbara, CA 93106-5050 USA; <sup>2</sup>Paul Scherrer Institut Wuerenlingen and Villigen, Laboratorium fuer Micro-Nanostrukturen, Villigen/PSI CH-5232 Switzerland; <sup>3</sup>University of California, Electl. Eng., 7549 Boelter Hall, Los Angeles, CA 90095-1594 USA

Materials for fast photoconducting devices must exhibit insulating dark behavior along with high photocarrier mobilities and short photocarrier carrier lifetimes. Shorter carrier lifetimes increase the speed of the photoconducting device while higher dark resistivities reduce background dark-current and allow the device to be operated at a high bias voltage. We report the growth by molecular beam epitaxy of composite epitaxial materials for these purposes consisting of layers of semi-metallic ErAs particles embedded in an  $In_{0.53}Ga_{0.47}As$  matrix. We have grown structures by molecular beam epitaxy on (100)-oriented semi-insulating InP:Fe substrates at 490°C. Transmission electron microscopy images show that the ErAs forms islands that have a thickness of  $14 \text{ \AA} \pm 3 \text{ \AA}$  (~4 monolayers) and varied in area depending on amount of ErAs deposited. The material was found to be n-type, but the electron charge was found to be inversely proportional to the ErAs deposition up to nearly the point where the islands coalesce. As the deposition of ErAs increases, the lateral size and density of the particles also increases, resulting in a more rapid freeze out of the electrons and reduction of the free electron concentration at 300K. We find the free electron concentration can be further reduced by compensation with beryllium, leading to more resistive material. Optimal Be doping and ErAs deposition yielded a sheet resistance of 2.4 M $\Omega$ / as calculated from Hall measurement data. Electric fields of over  $2 \times 10^5$  V/cm have been sustained in interdigitated finger structures with a spacing of 1  $\mu$ m in separation without breaking down the material. Dipole antenna photomixer devices optically pumped at 1.55  $\mu$ m have demonstrated photomixing up to 10 GHz. This work supported by DARPA/USAF Grant F33615-99-1-1514.

**11:40 AM Student**

**S5, Arsenic Incorporation in Si Molecular Beam Epitaxy:** Xian Liu<sup>1</sup>; Qiang Tang<sup>1</sup>; James S. Harris<sup>1</sup>; Theodore I. Kamins<sup>2</sup>; <sup>1</sup>Stanford University, Solid State & Photonics Lab, CIS-126X, Stanford, CA 94305 USA; <sup>2</sup>Hewlett-Packard Laboratories, Quantum Sci. Rsrch., 1501 Page Mill Rd., MS 1123, Palo Alto, CA 94304 USA

As MOSFETs scale to the deep-submicron scale, there has been an increasing demand for silicon epitaxial layers with abrupt doping profiles. For nanoscale devices arsenic is an attractive N-type dopant because of its high solubility and low diffusion rate, but suffers from surface segregation during epitaxy, making high-concentration incorporation with abrupt profiles difficult. In this paper we report the results of arsenic incorporation in Si molecular beam epitaxy (MBE) using a unique combination of solid (As, Si) and gas (disilane) sources to achieve these goals. Si epitaxy using disilane involves a series of surface reactions and requires substrate temperatures higher than 600°C to produce a useful growth rate. At these temperatures, As segregates severely to the growing surface, and also reduces the growth rate. The highest As concentration obtained using disilane in the present experiments was approximately  $5 \times 10^{17} \text{ cm}^{-3}$ , consistent with previous reports using similar growth temperatures but hydride precursors for both Si and As. Supplying Si from a solid source, on the other hand, eliminates the surface reaction steps and enables deposition at lower temperatures where As segregation is suppressed. Using a growth temperature of 400°C, As concentrations up to the mid- $10^{20} \text{ cm}^{-3}$  range were obtained. During growth at this temperature, in-situ reflection high-energy electron diffraction (RHEED) showed a slow development of 3-D characteristics in the Si pattern, indicating surface roughening. During heating of these samples to higher temperatures following deposition, the 3-D characteristics disappeared and (2 x 1) reconstruction appeared near 650°C, indicating smoothing of the surface. In contrast, samples deposited at 500°C with the same source fluxes did not show roughening, but had slightly lower As concentrations due to increased segregation. The temperature range in which this transition in growth mode occurs implies a possible connection with H desorption and Si-H bond breaking, which occur near 450°C. H is the most abundant background species in the vacuum and is known to induce surface roughening in low-temperature Si epitaxy. On the other hand, an increase of surface mobility on heating to 650°C, as indicated by surface smoothing, may be connected to desorption of chemisorbed As, which occurs near 700°C. As passivates Si surfaces and is expected to reduce surface mobility. Using a combination of solid and gas sources for Si epitaxial growth, we demonstrate for the first time Si (100) epilayers with As concentrations up to  $3.5 \times 10^{20} \text{ cm}^{-3}$  and doping transitions better than 50 and 20 Angstroms per decade at the start and end of As-doped growth, respectively. The measured transition width is limited by the depth resolution of SIMS. Parameter optimization may further increase

the maximum doping concentration. Preliminary cross-section TEM analysis did not show extended defects.

## Session T: Special Topical Session: Semiconductor Spintronics - II

Thursday AM Room: Corwin West  
June 27, 2002 Location: University of California

*Session Chairs:* Nicola Hill, University of California–Santa Barbara, Matls. Dept., Santa Barbara, CA 93106 USA; Leor Kronik, University of Minnesota, Dept. of Cheml. Eng. & Matls. Sci., 151 Amundson Hall, 421 Washington Ave. SE, Minneapolis, MN 55455-0132 USA

### 8:20 AM Invited

**T1, Epitaxial Growth and Properties of Ferromagnetic Co-Doped TiO<sub>2</sub>:** *Anatase S.A. Chambers<sup>1</sup>; C. Wang<sup>1</sup>; S. Thevuthasan<sup>1</sup>; T. Droubay<sup>1</sup>; D. E. McCready<sup>1</sup>; A. S. Lea<sup>1</sup>; C. F. Windisch, Jr.<sup>2</sup>; R. F.C. Farrow<sup>3</sup>; R. F. Marks<sup>3</sup>; J. U. Thiele<sup>3</sup>; A. J. Kellock<sup>3</sup>;* <sup>1</sup>Pacific Northwest National Laboratory, Fundamental Sci. Div., PO Box 999, MS K8-93, Richland, WA 99352 USA; <sup>2</sup>Pacific Northwest National Laboratory, Energy Tech. Div., PO Box 999, MS K8-93, Richland, WA 99352 USA <sup>3</sup>IBM Almaden Research Center, Magnetics Div., 650 Harry Rd., San Jose, CA 95120 USA

We are actively exploring the growth and physical properties of crystalline Co-doped TiO<sub>2</sub> anatase films grown on LaAlO<sub>3</sub>(001) substrates by oxygen plasma assisted molecular beam epitaxy (OPA-MBE)<sup>[1,2]</sup>. The resulting material is as or more strongly ferromagnetic than any known diluted magnetic semiconductor, and exhibits a Curie temperature of at least 500K. The moment per Co ion at saturation and remanence are 1.2-1.4  $\mu_B$  and ~30%, respectively, for temperatures up to 300K. Experiments are currently underway to determine in detail the dependence of the moment, remanence, and coercivity on temperature above 300K. The room temperature moment and remanence are approximately five and ten times larger, respectively, than those measured for analogous films grown by pulsed laser deposition<sup>[3]</sup>. We have found that a growth rate of 0.01 nm/sec and substrate temperatures in the range of 800K to 850K lead to single crystal anatase films with small mosaic spread. In contrast, the use of a higher growth rate (0.04 nm/sec) results in the formation of secondary nanocrystalline phases of TiO<sub>2</sub> rutile in which Co preferentially segregates. Single crystal anatase films grown at the lower growth rate contain substitutional Co(II) and are *n*-type semiconductors despite the absence of intentional *n*-type doping. Preliminary evidence suggests that *n*-type doping comes about because of hydrogen reduction of anatase during growth by residual hydrogen in the MBE chamber. This process leads to substitutional OH in the crystalline lattice at the 10<sup>19</sup> to 10<sup>20</sup> cm<sup>-3</sup> level, and free electrons that occupy a shallow donor band. Furthermore, we find that the magnetization is directly proportional to the conductivity. Thus, Co-doped anatase appears to be magnetic by virtue of *electron* mediated exchange interaction. There are also oxygen anion vacancies that accompany substitutional Co(II) in the lattice in order to maintain local charge neutrality. These oxygen anion vacancies are uncharged and, therefore, do not contribute free carriers. <sup>1</sup>S. A. Chambers, S. Thevuthasan, R. F.C. Farrow, R. F. Marks, J.-U. Thiele, L. Folks, M. G. Samant, A. J. Kellock, N. Ruzycski, D. L. Ederer, and U. Diebold, *Appl. Phys. Lett.* 79, 3467 (2001); <sup>2</sup>S. A. Chambers, *Mat. Today*, to appear in the April 2002 issue; <sup>3</sup>Y. Matsumoto, M. Murakami, T. Shono, T. Hasegawa, T. Fukumura, M. Kawasaki, P. Ahmet, T. Chikyow, S.-Y. Koshihara, and H. Koinuma, *Science*, 291, 854 (2001).

### 9:00 AM

**T2, Electric-Field Effects on Spin Diffusion and Enhancement of Spin Injection into Semiconductors:** *Zhi G. Yu<sup>1</sup>; Michael E. Flatte<sup>1</sup>;* <sup>1</sup>University of Iowa, Dept. of Physics & Astron., Iowa City, IA 52242 USA

In previous theoretical studies of spin transport and injection in semiconductors the spin polarization is usually assumed to obey the same diffusion equation as in metals,  $\tilde{\nabla}^2(\mu_{\uparrow}-\mu_{\downarrow})-L^2=0$ , (1) where  $\mu_{\uparrow}$  is the electrochemical potential of up-spin (down-spin) electrons. In this

diffusion equation, the electric field does not play any role. This equation is reasonable for metals because the electric field *E* is essentially screened. For semiconductor spintronic devices, however, the semiconductor often is lightly doped and nondegenerate, and a moderate electric field can dominate the carrier motion. We obtain a more general drift-diffusion equation for spin polarization in a semiconductor,  $\tilde{\nabla}^2(n_{\uparrow}-n_{\downarrow})+eE \cdot \tilde{\nabla}(n_{\uparrow}-n_{\downarrow})/k_B T-(n_{\uparrow}-n_{\downarrow})/(L^{(s)})^2=0$ , (2) where  $n_{\uparrow}-n_{\downarrow}$  is the difference between up-spin and down-spin electron densities and  $L^{(s)}$  is the intrinsic spin diffusion length. The above equation consistently takes into account electric-field effects and nondegenerate electron statistics and provides a framework to understand spin transport in semiconductors. We identify a high-field diffusive regime that has no analogue in metals. This regime occurs for fields as small as 1 V/cm at low temperatures. In this regime two distinct spin-diffusion lengths characterize spin motion, i.e., up-stream ( $L_u$ ) and down-stream ( $L_d$ ) spin diffusion lengths, which can differ in orders of magnitude with realistic fields:  $E \approx 2.5$  V/cm at  $T = 3$  K and  $E \approx 250$  V/cm at  $T = 300$  K. As an application of the more general drift-diffusion equation for spin transport in semiconductors, we study how the electric field affects spin injection from a ferromagnetic metal to a semiconductor. We find that the spin injection in the semiconductor,  $\hat{a}(x) \propto [j_{\uparrow}(x)-j_{\downarrow}(x)]/J$ , can be described in terms of the two field-induced diffusion lengths,  $\hat{a}(x) = [L^{(s)}/(1-p^2)\delta_f + L_d/\delta_s]^{-1} p_f L^{(s)} e^{-x/L} / (1-p^2)\delta_f$ , (3) where  $p_f = (\delta_f - \delta_s)/\delta_f$  is the spin polarization in the metal, and  $\delta_f$  ( $\delta_s$ ) is the conductivity of the metal (semiconductor). We see that both diffusion lengths affect spin injection favorably but in a different manner. The up-stream length  $L_u$  controls the relevant resistance in the semiconductor, which determines the spin injection efficiency. With increasing field this effective resistance,  $L_u/\delta_s$ , becomes smaller and accordingly the spin injection efficiency is enhanced. The transport distance of the injected spin polarization in the semiconductor, however, is controlled by the down-stream length  $L_d$ . As the field increases this distance becomes longer. The spin injection obtained by previous calculations based on Eq. (1) is simply the zero-field result of Eq. (3), where both  $L_u$  and  $L_d$  are substituted by the intrinsic length  $L^{(s)}$ . Our results indicate that the resistance mismatch obstacle may be overcome with the help of strong electric fields because the effective semiconductor resistance to be compared with  $L^{(s)}/\delta_f$  should be  $L_d/\delta_s$  rather than  $L^{(s)}/\delta_s$  and  $L_u$  can be smaller than  $L^{(s)}$  by orders of magnitude in the high-field regime.

### 9:20 AM

**T3, Spin Coherent Electron Injection in a Self Assembled Nanowire with Ferromagnetic Nanocontacts: A Novel Route to Single Qubit Rotation in a Quantum Gate:** *Supriyo Bandyopadhyay<sup>1</sup>; Shouvik Datta<sup>2</sup>; Latika Menon<sup>2</sup>;* <sup>1</sup>Virginia Commonwealth University, Electl. Eng., Richmond, VA 23284 USA; <sup>2</sup>University of Nebraska, Electl. Eng., Lincoln, NE 68588-0511 USA

We have produced tri-layered nanowires of Fe-CdS-Ni and Fe-CdS-Co by electrodepositing the constituents sequentially into the pores of a self-assembled alumite template that has either 8- or 50-nm diameter pores. The length of the nanowires is 0.1-0.5 microns. The varying length is a fortuitous happenstance; it allows us to expose the tips of very few wires by carefully etching the alumina template from the front and back. This critical step allows us to contact relatively few nanowires by large-area "non-alloyed" contact pads defined by conventional photolithography. Current-voltage measurements have shown room temperature Coulomb blockade, and (in multi-grained wires) room temperature Coulomb staircase under infrared illumination, indicating that indeed very few wires are electrically contacted by these large area pads. By comparing the capacitance estimated from the Coulomb blockade region with that measured by C-V measurements carried out using silver paint contacts (which diffuse and contact virtually every nanowire), we estimate that, on the average, one in a million nanowire is electrically contacted! This eliminates the need for a nanocontact, such as an STM tip, for probing few wires at a time. The tri-layered nanowire structure is inspired by a proposal for a universal quantum XOR gate. An electron will be injected into the semiconductor layer from a ferromagnetic contact that acts as a spin polarizer. The spin will encode a qubit. Unitary rotations on the qubit will be carried out by exploiting the Rashba spin splitting effect and an ac magnetic field (S. Bandyopadhyay, *Phys. Rev. B*, Vol. 61, 13813 (2000)). The qubit (spin orientation) is read by applying a bias and monitoring the transmitted charge through the other ferromagnetic contact that acts as a spin-analyzer (or filter). We have measured the current through 20 or so trilayered nanowires in parallel (con-

tacted by large area pads) as a function of a longitudinal magnetic field at 4.2 K. Previous SQUID measurements have shown that 8-nm Fe, Ni and Co nanowires have coercivities of 4000 Oe, 2500 Oe and 700 Oe respectively at 4.2 K. At a high magnetic field, both the polarizer and analyzer are magnetized along the field direction and current flows. As the field is reversed, the ferromagnet with the lower coercivity (Ni or Co) flips magnetization first and the current drops because the polarizer and analyzer are anti-aligned. Finally, the Fe also flips and the current rises again. We have distinctly observed the magnetoresistance peak due to this effect. It has not been washed out by ensemble averaging since we are measuring only about 20 nanowires. This experiment shows that the spin polarizer (qubit “writer”) and spin analyzer (qubit “reader”) are working. We are also able to coherently inject spin from a metallic ferromagnet (with only about 40% spin polarization) into a semiconductor probably because of the small area (8-nm) interface. In conclusion, this research sheds new light on the physics of spin injection in one-dimensional structures and also paves the way for a quantum XOR gate.

#### 9:40 AM

**T4, Tunability of Electron Spin Coherence in Semiconductor Nanostructures:** *Wayne H. Lau*<sup>1</sup>; Michael E. Flate<sup>1</sup>; <sup>1</sup>University of Iowa, Dept. of Physics & Astron., 117 IATL, Iowa City, IA 52242 USA

Modern solid-state electronics relies on the precise control of electronic charge. Recently, however, there has been intense interest in incorporating electron spin degree of freedom into electronic semiconductor devices-spintronics. This has led to new ultrafast optical studies of electron spin dynamics in semiconductor nanostructures. One of the important factors in utilizing coherent spin dynamics in electronic devices is that the spin coherence time must be sufficiently long so that information stored in the spin polarized ensembles will not be lost during processing. Another essential requirement for such spin-dependent devices is the ability to manipulate electron spin coherence. Electron spin coherence times in III-V semiconductor nanostructures near room temperature are dominated by the precessional D’yakonov-Perel’ (DP) mechanism, which is a direct result of the spin splitting of the conduction band that occurs at zero magnetic field at finite crystal momentum in inversion asymmetric crystals. In semiconductor nanostructures such as quantum wells (QWs), this inversion asymmetry can arise not only from bulk inversion asymmetry (BIA) of the constituent semiconductors, but also from structure inversion asymmetry (SIA) of an asymmetric potential. The effect of BIA is dominant in structural symmetric QWs. On the other hand, in asymmetric QWs (e.g., in the presence of external electric field along the growth direction), the contribution to electron spin decoherence due to SIA may become important. Hence the application of applied electric field can be used to manipulate spin coherence times in QWs. We have calculated both T1 and T2 for (110)-oriented GaAs/AlGaAs QWs near room temperature. The altered symmetry of (110)-oriented QWs leads to an increase in calculated spin coherence times (T1) compared to those of similar (001)-oriented QWs and exceeds one nanosecond at room temperature. We have also studied the electron spin coherence times under applied electric field along the growth direction in (001)- and (110)-oriented GaAs/AlGaAs QWs. T1 is considerably more responsive to the growth-direction electric field in (110)-oriented QWs than in (001)-oriented QWs, whereas the response of T2 is similar for both growth directions. We found that there is a strong in-plane anisotropy of electron spin decoherence in (001)-oriented QWs in the presence of applied electric field along the growth direction. We have also calculated both T1 and T2 for a (001)-oriented GaAs/AlGaAs parabolic QW, and the results are consistent with the recent measurements.

#### 10:00 AM Break

#### 10:20 AM Student

**T5, Fe<sub>1-x</sub>Co<sub>x</sub>/GaAs Interfaces: Growth, Interfacial Reactions and Spin Polarized Transport:** *B. D. Shultz*<sup>1</sup>; A. F. Isakovic<sup>2</sup>; J. Strand<sup>2</sup>; K. Lüdge<sup>1</sup>; P. A. Crowell<sup>2</sup>; C. J. Palmström<sup>1</sup>; <sup>1</sup>University of Minnesota, Cheml. Eng. & Matls. Sci., Minneapolis, MN 55455 USA; <sup>2</sup>University of Minnesota, Sch. of Physics & Astron., Minneapolis, MN 55455 USA

Defects and interfacial magnetic dead layers at ferromagnet/semiconductor interfaces will result in spin randomizing scattering and reduced spin injection efficiency. Hence, control of the interfacial properties and reactions of epitaxial ferromagnetic metals and semiconductors is important for optimizing spin dependent transport across these interfaces. In-situ AES and XPS of MBE grown Fe deposited on GaAs indicates signifi-

cant reduction in the Fe-Ga-As reaction by lowering the growth temperature below 100°C. For Co even lower growth temperatures are required to limit the Co-Ga-As reactions. Sc<sub>1-y</sub>Er<sub>y</sub>As interlayers have been used to further reduce these ferromagnet-Ga-As reactions. In-situ STM images show preferential attachment of the Fe<sub>x</sub>Co<sub>1-x</sub> atoms on the GaAs while no preferential attachment occurs on the Sc<sub>1-y</sub>Er<sub>y</sub>As interlayers. In order to measure the injection of spin polarized carriers from epitaxial Fe<sub>x</sub>Co<sub>1-x</sub> contacts into Ga<sub>1-x</sub>Al<sub>x</sub>As, quantum well spin LED structures were fabricated. Reverse biased tunneling Schottky contacts were used for the spin injectors to circumvent the inherent problems associated with spin injection using diffusive transport contacts. Optimization of the semiconductor LED structures was undertaken in order to improve the efficiency of polarized light emission. The electroluminescence polarization as a function of wavelength, electrical bias, magnetic field and temperature was measured and compared with the photoluminescence under identical conditions for both ferromagnetic Fe/Ga<sub>1-x</sub>Al<sub>x</sub>As and nonmagnetic Al/Ga<sub>1-x</sub>Al<sub>x</sub>As LED structures. The wavelength dependence allows the separation of contributions from heavy hole, light hole and impurity state transitions to be determined. This paper will emphasize the structure and the extent of interfacial reactions of Fe<sub>1-x</sub>Co<sub>x</sub>/GaAs as a function of growth temperature and the measurement of spin polarized transport across the Fe<sub>1-x</sub>Co<sub>x</sub>/Ga<sub>1-x</sub>Al<sub>x</sub>As interface. This work was supported in part by ONR N/NO0014-99-1-0233, DARPA/ONR N/NO001499-1-1005, N/NO0014-01-1-0830, and NSF-MRSEC NSF/DMR-9809364.

#### 10:40 AM

**T6, Direct Spin Injection from a Ferromagnetic Metal into a Semiconductor Through Fe/InAs Junction:** *Kanji Yoh*<sup>1</sup>; Hiroshi Ohno<sup>2</sup>; Yoshito Katano<sup>1</sup>; Kazuhisa Sueoka<sup>2</sup>; Koichi Mukasa<sup>2</sup>; <sup>1</sup>Hokkaido University, Rsrch. Ctr. for Integrated Quantum Elect., Sapporo 060-8628 Japan; <sup>2</sup>Hokkaido University, Grad. Sch. of Eng., Sapporo 060-8628 Japan

Electron spin is attracting much interest in semiconductors in the hope that the manipulation of the spin-entangled state in semiconductors would eventually lead to a quantum computer<sup>1</sup> with a semiconductor chip. The question is how to inject spin-polarized electrons into semiconductors. So far, spin injection from diluted magnetic semiconductors (DMS) has been reported, with the injection efficiency of ~1%. Unfortunately, these DMS materials have rather low Curie temperatures (Tc). On the other hand, spin injection from high Tc ferromagnetic metals has not been successful for such a long time. Recently, however, approximately 2%-efficient spin-injection was demonstrated in Fe/GaAs system where electrons tunnel through a Schottky barrier which seems to play a critical role to overcome the mobility mismatch problem as suggested by Rashba. However, such a tunnel barrier would limit the drain current drastically. Here we show that the spin injection is possible without a tunneling barrier in Fe/InAs hybrid structure with the injection efficiency of 3.6 ~ 4.1%. The crystal quality bcc Fe thin film was grown on zinc-blend p-type InAs wafer in a ultra-high-vacuum (UHV). Fe film was patterned into line/space array (width: w = 2µm, pitch: p = 4µm,) so that it would bear a clear magnetic anisotropy upon magnetization. When the sample is forward biased and the flat-band condition is met, ballistically injected electrons readily recombine with holes in the p-type InAs and emit photons. The polarization of the electroluminescent light is detected in the direction parallel to the Fe wires along which the electron spin is aligned. Thus, the intensity ratio of the two kinds of the circularly polarized light (clockwise or anticlockwise) would represent the electron spin polarization in the semiconductor. A clear electro-luminescence was detected from the cleaved edge of the InAs sample by the InSb photo-detector. The &#61555;&#61483;&#61472; and &#61555; &#61485; &#61472; components of the luminescence were measured by switching the angle of the quarter-wave plate. Prior to the measurement, the sample was magnetized in the wire direction at the field of 3000 Oe. A clear difference between the &#61555;&#61483;&#61472; and &#61555; &#61485; &#61472; component was observed and the polarization of the luminescence PL was found to be 3.6% ~ 4.1%. Considering that the electron spin polarization in the Fe electrode is estimated to be 28% (11%) as described above, the measured spin polarization value of injected electrons is already sufficiently large. These results clearly indicate that the spin injection in the FM/SC hybrid system is possible without a tunneling barrier despite the contradictory arguments based on conductivity mismatch.

11:00 AM

**T7, Spin-Spin Interaction in Magnetic Semiconductor Quantum Dots:**

*Gerd Bacher*<sup>1</sup>; J. Seufert<sup>1</sup>; H. Schoemig<sup>1</sup>; M. Scheibner<sup>1</sup>; A. Forchel<sup>1</sup>; A. A. Maksimov<sup>2</sup>; V. D. Kulakovskii<sup>2</sup>; A. V.V. Chernenko<sup>2</sup>; S. Lee<sup>3</sup>; M. Dobrowolska<sup>4</sup>; J. K. Furdyna<sup>4</sup>; <sup>1</sup>University of Wuerzburg, Technische Physik, AM Hubland, Wuerzburg 97074 Germany; <sup>2</sup>RAS, Inst. of Solid State Physics, Moscow Reg., Chernogolovka 142432 Russia; <sup>3</sup>Korea University, Dept. of Physics, 5-Ka Anam-dong, Seoul 136-701 Korea; <sup>4</sup>University of Notre Dame, Dept. of Physics, 225 Nieuwland Science Hall, Notre Dame, IN 46556 USA

The application potential of magnetic semiconductor quantum dots in spintronics result from the possibility to combine the discrete density of states of a quasi-zero dimensional *electronic* system with the ability to control the *magnetic* properties on a nanometer scale. The challenge in fabricating such structures, however, has up to now prevented a detailed understanding of the interaction between charge particles and magnetic ions and the limits of such nanomagnetic devices. We have studied the spin-spin interaction between carrier spins and the spins of magnetic ions in self-assembled CdSe/ZnMnSe quantum dots by using optical spectroscopy with high temporal and high spatial resolution, respectively. As the energy of a single electron-hole pair sensitively depends on the spin alignment of the magnetic ions within the exciton wavefunction (in our case a few hundred), variations of the nanoscale magnetization result in a characteristic change of the PL signal<sup>1</sup>. Following the transient photoluminescence (PL) signal of the quantum dot after pulsed laser excitation thus allows to monitor the magnetization dynamics on a picosecond time scale<sup>2</sup>. We obtain a typical spin response time of 130 ps at T = 2K, which only slightly increases with temperature and magnetic field. This indicates, that future devices based on the spin-spin interaction in magnetic quantum dots may operate even in regime of several GHz. On the other hand, a thermodynamical limit for operating such nanomagnetic devices arises if one proceeds to ultrasmall magnetic systems: Statistical magnetic fluctuations are expected to restrict the device functionality. We have studied the magnetization on a 10 nanometer scale by optically addressing single self-assembled CdSe/ZnMnSe quantum dots. In spite of the  $\delta$ -like density of states in a quantum dot, we found a rather large emission linewidth, which strongly narrows by applying a magnetic field. This is demonstrated to result from statistical magnetic fluctuations in the single dot, which are suppressed in an external magnetic field due to the Mn<sup>2+</sup> spin alignment. i.e., statistical magnetic fluctuations within the scale defined by the exciton radius are probed via the optical response of a single magnetic quantum dot. <sup>1</sup>G. Bacher et al.; Appl. Phys. Lett. 79, 524 (2001); <sup>2</sup>J. Seufert et al., Phys. Rev. Lett. 88, 027402 (2002).

11:20 AM

**T8, Field Effect Magnetization Reversal in Ferromagnetic Semiconductor Quantum Wells:** *Byounghak Lee*<sup>1</sup>; Tomas Jungwirth<sup>1</sup>; Allan H. MacDonald<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Dept. of Physics, Austin, TX 78712 USA

We demonstrate a novel field effect magnetization reversal in diluted magnetic semiconductor quantum wells. We consider a (II,Mn)VI quantum wells, where the Mn concentration and the itinerant hole density can be varied independently. Our calculation is based on a mean-field theory derived in the spin-density-functional framework. The Hamiltonian is written using an envelope function description of valence band electrons and a spin representation of their kinetic-exchange interaction with d-band electrons on the Mn ions. The calculation of magnetic hysteresis shows changes in the coercive field under applied electric field. The coercivity is decreased with a positive bias and increased with a negative bias. This unusual effect is understood as a field effect magnetization reversal process as following. When all local spins are polarized in one direction, e.g. in the negative z-direction, spin-up holes are the majority carriers at zero external magnetic field because of the antiferromagnetic p-d coupling. If the 2D hole densities is low enough, itinerant system is fully polarized. When the magnetic field is applied, direct Zeeman coupling to a local moment competes with the local mean-field kinetic-exchange coupling which is proportional to the itinerant-hole spin-density. Since the carrier density is smaller at the edges of the quantum well than at the center, local spin reversal starts from the well edges. This, in turn, creates an exchange barrier for the majority-spins which effectively narrows the quantum well in which they reside. At the same time an effective double-well potential develops for the minority spins. As the external magnetic field increases, the minority-spin energy levels are

lowered and the majority-spin energy levels are raised. When the lowest down-spin energy level reaches the Fermi energy, holes start to occupy the down-spin states. Our calculations show that once this occurs, the magnetization reversal is rapidly completed and only the uniform down-spin state is stable. The modification of hysteresis curve by applied electric field is due to this unusual process in which magnetization reversal and quantum confinement effects. The external electric field contributes to the change of the hysteresis loop in two ways. First, the hole-density profile is compressed and moves toward one edge of the well, permitting an abrupt localized moment reversal throughout the depleted region of the quantum well. Second, the increase (decrease) of the 2D hole density enhances (suppresses) the kinetic-exchange coupling. The interplay between quantum confinement and magnetization reversal in ferromagnetic semiconductor quantum wells is reflected in unusual magnetocapacitance effects. The inverse capacitance is the sum of the inverse geometric capacitance, which depends only on the distance from the quantum well to the gate, and the inverse 2D-channel capacitance, which reflects the electronic structure of the 2D hole gas. Our calculation shows a similarity of electric and magnetic responses, suggesting that capacitance measurements can be used to probe the magnetic state of biased ferromagnetic semiconductor quantum wells.

11:40 AM

T9, Late News

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## Session U: Silicon Carbide: Growth

Thursday AM  
June 27, 2002

Room: Corwin East  
Location: University of California

*Session Chair:* Robert Stahlbush, Naval Research Laboratory, Code 6813, Washington, DC 20375 USA

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8:20 AM

**U1, Comparison of N-Type SiC Epitaxial Layers Grown Using Phosphine and Nitrogen as the Precursors:** Rongjun Wang<sup>1</sup>; *Ishwara Bhat*<sup>1</sup>; Paul Chow<sup>1</sup>; <sup>1</sup>Rensselaer Polytechnic Institute, ECSE Dept., JEC 6049, Troy, NY 12180 USA

Nitrogen has been the most common n-type dopant in SiC. In this work, we have carried out a comparative study of n-type SiC epitaxial layers grown in a cold wall CVD reactor using phosphine and nitrogen as the precursors. The doping dependencies on precursor flow rate; growth temperature and C/Si ratio are investigated. Thermodynamic simulations for analysis of the gas phase composition under growth conditions were also performed to help understand the incorporation mechanisms. Substrates used for this study were 3.5° off-axis towards <11-20>, (0001) Si-face 6H-SiC and 8° off-axis towards <11-20>, (0001) Si-face 4H-SiC from Cree Research, Inc. Doping concentration was characterized by mercury probe CV measurement and SIMS. This is the first detailed study of phosphorous-doped SiC grown by CVD. The influence of precursor flow on doping concentration was investigated at 1560°C. The experiments showed that the increase of Nd-Na is proportional to [PH<sub>3</sub> flow rate]<sup>0.5</sup> for phosphorous-doped growth and [N<sub>2</sub> flow rate]<sup>0.9</sup> for nitrogen-doped growth when the respective precursor flow rate is relatively higher. Thermodynamic simulation showed that at the growth condition, P<sub>2</sub>, PH and P are the most abundant species in the gas phase for the P-doped growth and N<sub>2</sub>, HCN and HNC are the most abundant species for the N<sub>2</sub> doped growth. The simulation also showed that if Henry's law<sup>[1]</sup> is applicable in our situations, the phosphorous concentration and the nitrogen concentration in the epilayers are expected to be proportional to [PH<sub>3</sub> flow rate]<sup>0.5</sup> and [N<sub>2</sub> flow rate]<sup>0.5-0.7</sup>, respectively. While phosphorous doping behaved according to the theoretical prediction, nitrogen doping increased faster than expected, which was explained by the site-competition between C and N during the growth. Study on the effect of growth temperature showed that nitrogen doping increased with temperature with activation energy of 91 kcal/mol and phosphorous doping decreased with temperature. The increase of nitrogen incorporation with temperature was caused by the increased surface reaction and the decrease of phosphorous doping was likely caused by the en-



hanced desorption of phosphorous-containing species on the growth surface. The study of site-competition growth was performed by varying C/Si ratio during the growth. It was shown that while nitrogen doping increased dramatically with the reduced C/Si ratio, phosphorous doping was hardly affected by C/Si especially when C/Si is higher than 3 or lower than 0.8 (ideal condition to get more uniform growth). When C/Si is between 0.8 and 3, phosphorous doping increased slightly with decreased C/Si. For nitrogen doping, this result is consistent with the site-competition theory reported by D. J. Larkin<sup>[2]</sup>. However, it is different in case of the phosphorous-doped growth. Our result seems to suggest that phosphorous might occupy C site at certain growth conditions. (supported by ERC program of the NSF under award #EEC-9731677). References: <sup>[1]</sup>J. Zhang, A. Ellison, A. Henry, M. K. Linnarsson and E. Janzen. *J. Crystal Growth* 226 (2001), p.267; <sup>[2]</sup>D. J. Larkin. *Phys. Stat. Sol. B* 202 (1997), p.305.

#### 8:40 AM

**U2, Characterization of 3C-SiC Layers Grown During Step-Free Surface Heteroepitaxy:** *Philip G. Neudeck*<sup>1</sup>; J. A. Powell<sup>1</sup>; David J. Spry<sup>2</sup>; Andrew J. Trunek<sup>2</sup>; Xianrong Huang<sup>3</sup>; William M. Vetter<sup>3</sup>; Michael Dudley<sup>3</sup>; Marek Skowronski<sup>4</sup>; Jinqiang Liu<sup>4</sup>; <sup>1</sup>NASA Glenn Research Center, Instrumentation & Controls Div., 21000 Brookpark Rd., Cleveland, OH 44135 USA; <sup>2</sup>OAI, NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135 USA; <sup>3</sup>State University of New York at Stony Brook, Dept. of Matls. Sci. & Eng., Eng. Bldg., Stony Brook, NY 11794 USA; <sup>4</sup>Carnegie Mellon University, Matls. Sci. Dept., 5000 Forbes Ave., Pittsburgh, PA 15213 USA

A recently reported growth process named step-free surface heteroepitaxy achieved 3C-SiC films completely free of double positioning boundaries (DBP's) and stacking faults (SF's) on 4H-SiC and 6H-SiC substrate mesas. The process was carried out on arrays of device-sized mesas produced on commercial 4H- or 6H-SiC "on-axis" substrates, wherein the top (0001) basal plane surface of each screw-dislocation free mesa is rendered entirely free of atomic steps via homoepitaxial stepflow growth as described in. By lowering the growth temperature in-situ to promote two-dimensional (2D) nucleation on the step-free (0001) 4H or 6H basal plane, heteroepitaxial growth of 3C-SiC is thermodynamically favorable in the absence of kinetic step-control to replicate substrate polytype. The step-free surface heteroepitaxy process is also based upon low (but nonzero) nucleation rates for the initial stages of heterofilm growth. Initial high rates of heterofilm nucleation (induced by large rapid decrease in growth temperature at the initiation of heterofilm growth) yielded 3C-SiC films with SF defects. In contrast, 3C-SiC films initiated at lower nucleation rates (resulting from smaller and/or less rapid temperature decreases) were entirely free of SF defects. While we have attributed the SF defect formation to defective coalescence of multiple nucleated islands on the growth surface, important questions remain as to the exact nature of the growth and defect formation. This paper reports detailed characterization of both ideal (i.e., entirely free of DPB's and SF's) and non-ideal 3C-SiC heterofilms by a number of methods. In particular, the 3C-SiC films have been studied by Synchrotron White Beam X-ray Topography (SWBXT), High Resolution X-ray Diffraction (HRXRD), High Resolution Cross-sectional Transmission Electron Microscopy (HRXTEM), Atomic Force Microscopy (AFM), molten KOH etching, and thermal oxidation. The experimental results confirm that the local stacking sequence of the top two substrate bilayers thermodynamically controls which twin-variant of 3C-SiC nucleates on a 4H- or 6H-SiC (0001) basal plane. HRXTEM of an ideal mesa shows an abrupt, step-free 3C/4H heterointerface with a pure 3C-SiC layer free of dislocations and stacking disorder within the field of view. Small-beam HRXRD reciprocal mapping reveals extremely high crystalline perfection and homogeneity of the 3C-SiC epilayers. The out-of-plane and in-plane lattice mismatch parameters of the 3C/4H heterostructure were measured at -0.138% and 0.0116%, respectively. The measured in-plane mismatch implies that some strain relaxation occurred in the 3C-SiC epilayers, many of which are much thicker than the critical thickness for pseudomorphic film strain relief calculated from previously published 3C and 4H material parameters. In addition to delineating DBP and SF defects previously revealed by thermal oxidation on non-ideal mesas, molten KOH etching produced some isolated triangular pits on many ideal mesas suggesting the presence of isolated dislocations.

#### 9:00 AM

**U3, Electrical and Structural Properties of Al-Doped 4H-SiC Epitaxial Layers-Grown by Hot-Wall CVD:** *Günter Wagner*<sup>1</sup>; Klaus Irmischer<sup>1</sup>; Wolfram Leitenberger<sup>1</sup>; Michael Wilde<sup>1</sup>; <sup>1</sup>Institute of Crystal Growth, Max-Born-Str. 2, Berlin 12489 Germany

The success of silicon carbide (SiC) for high temperature and high power electronic applications depends on the ability to reproducibly attain high-quality SiC epitaxial layers. High-voltage bipolar devices require thick epitaxial layers with a low background doping concentration, reproducible n- and p-type doping concentrations and a long carrier lifetime. In order to obtain a reasonable yield from the material, it is essential that the density of crystallographic defects and impurities are minimised. High growth rates are also desirable. In this study we investigate the incorporation of aluminium in 4H-SiC epitaxial layers using a commercial horizontal hot-wall system. In particular we concentrate our work on the dependence of the Al-concentration in the layers and their surface morphology on the growth parameters C/Si ratio, Al-concentration in the gas phase, growth temperature and silane flow. The incorporation of aluminium during epitaxial growth has been studied in the concentration range from  $1 \times 10^{15} \text{ cm}^{-3}$  to  $2 \times 10^{20} \text{ cm}^{-3}$ . Epitaxial growth was performed using silane (2% diluted in  $\text{H}_2$ ) and propane (5% diluted in  $\text{H}_2$ ) as process gases and trimethylaluminium (TMA) as doping source. Commercial 4H-SiC (0001) substrates off-oriented  $8^\circ$  towards  $\langle 11\bar{2}0 \rangle$  (Cree Res. Inc, SiCrystal) were used. Before loading into the Hot-Wall CVD reactor the substrates were cleaned according to the RCA procedure followed by immersion in a HF solution in order to remove the surface oxide. The substrates were etched in hydrogen atmosphere at  $1550^\circ\text{C}$  adding a small quantity of propane to reduce the surface roughness and to remove a residual surface damage layer immediately before layer deposition. In accordance with the site competition mechanism the unintentional N incorporation can be controlled by the C/Si ratio. The expected suppression of the N incorporation with increasing C/Si ratio was observed. For a C/Si ratio of 2, the N concentration is already lowered down to  $2 \times 10^{14} \text{ cm}^{-3}$ . Therefore the compensation by unintentional nitrogen doping can be neglected in the investigated p-type doping range. The chemical Al concentration was measured by secondary ion mass spectroscopy (SIMS) whereas the electrically active doping concentration was determined by capacitance-voltage (C-V) and Hall effect measurements. The absolute values of the chemical Al concentration exceeded those of the net acceptor concentration by an average factor of 2.5. Up to an acceptor concentrations  $N_A - N_D < 1 \times 10^{18} \text{ cm}^{-3}$  the Al-acceptor concentrations determined by Hall effect agree well with the C-V data. The Al-doped epitaxial layers up to  $1 \times 10^{19} \text{ cm}^{-3}$  showed very smooth, mirror like surfaces. At higher Al-doping concentration the surface morphology was characterised by increasing roughness. The investigation of high Al-doped epitaxial layers up to  $10^{20} \text{ cm}^{-3}$  by TEM showed no precipitations or inclusions of Al in the grown layers. Also Al-related structural defects were not visible.

#### 9:20 AM Student

**U4, Characterization of Undoped and Nitrogen-Doped 4H-SiC Thin Films by CVD from Bis-trimethylsilylmethane Single Precursor:** *Jae Kyeong Jeong*<sup>1</sup>; Myung Yoon Um<sup>1</sup>; Hoon Joo Na<sup>1</sup>; In Bok Song<sup>1</sup>; Hyeong Joon Kim<sup>1</sup>; <sup>1</sup>Seoul National University, Sch. of Matls. Sci. & Eng., San 56-1 Shillim-dong, Kwanak-gu, Seoul 151-742 S. Korea

High quality 4H-SiC epitaxial films were successfully grown on  $8^\circ$  off-axis (0001) 4H-SiC substrates by horizontal cold-wall chemical vapor deposition (CVD) from bis-trimethylsilylmethane [ $((\text{CH}_3)_2\text{Si})_2\text{CH}_2$ , BTMSM] single precursor. BTMSM has the advantage of the non-toxic and non-flammable source, compared to  $\text{SiH}_4$ , which is conventional gas source for Si supply. Full-width-at-half-maximum (FWHM) of (0004) Bragg spot of epi-layer grown at  $10 \text{ H}_2$  carrier gas flow rate of BTMSM, 1653K was  $9.7 \text{ arcsec}$ , while that of substrate was approximately  $15 \text{ arcsec}$ . The electrical properties of undoped and nitrogen-doped 4H-SiC epitaxial films grown at this condition were investigated by C-V measurement, Hall measurement, SIMS, and low temperature photoluminescence (LTPL). Unintentionally doped 4H-SiC films were always n-type semiconductor. The carrier concentration of the undoped epi-layers was strongly influenced by the graphite susceptor. When using the graphite susceptor, the doping level of the epi-layers varied from  $2.7 \times 10^{19}$  to  $2.7 \times 10^{20} \text{ cm}^{-3}$ . LTPL spectrum of these films show that nitrogen impurity is incorporated in the as-grown SiC films, indicating that this unusual high doping level might be attributed to out-diffusion of nitrogen from



the graphite susceptor during CVD growth. In order to prevent this out-diffusion of nitrogen impurity from the graphite susceptor, SiC coated graphite susceptor was used. The auto-doping level can be reduced to  $6.8 \times 10^{16} \text{ cm}^{-3}$  with electron mobility of  $324 \text{ cm}^2/\text{Vs}$ . The variation of free electron concentration for 4H-SiC film with a concentration of  $6.8 \times 10^{16} \text{ cm}^{-3}$  in the temperature ranges from 90 to 400K was measured by Hall effect measurement. From a least square fit of the neutrality equation to the experimental carrier concentration over the entire temperature range, the estimated ionization energies of the donor levels were 42.5 and 112.1 meV, respectively. The carrier concentration dependence of the electron mobility for the unintentionally doped SiC epi-layers was investigated. The electron mobility decreases with the higher carrier concentration, which is general relationship between the electron mobility and carrier concentration. The background doping level was further decreased by adjusting of the chamber pressure and Si/C ratio. As the chamber pressure decreased from 360 to 180 torr, the carrier concentration of undoped epi-layers also decreased from  $6.8 \times 10^{16}$  to  $2.0 \times 10^{16} \text{ cm}^{-3}$ . Moreover,  $\text{CH}_4$  addition of 2 sccm in the chamber at 180 torr resulted in the reduction of the carrier concentration to  $5 \times 10^{15} \text{ cm}^{-3}$ , which can be explained by "site-competition effect". As the flow rate of nitrogen gas ( $\text{N}_2$ ) was increased, the electron concentration of epi-layers linearly increased. With independent control and variation of  $\text{N}_2$  flow rate and Si/C ratio, the total n-doping range from about  $1 \times 10^{16}$  to  $2 \times 10^{20} \text{ cm}^{-3}$  was achieved.

9:40 AM

U5, Late News

10:00 AM Break

10:20 AM

**U6, P- and N-Type Doping of Silicon Carbide Single Crystals Using a Modified Physical Vapor Transport Technique:** *Peter J. Wellmann*<sup>1</sup>; Thomas L. Straubinger<sup>1</sup>; Patrick Desperrier<sup>1</sup>; Roland Weingärtner<sup>1</sup>; Albrecht Winnacker<sup>1</sup>; <sup>1</sup>University of Erlangen, Matls. Dept. 6, Martensstr. 7, Erlangen 91058 Germany

Silicon carbide (SiC) single crystals for commercial applications are currently grown by the so called physical vapor transport (PVT) method at elevated temperatures ( $T > 2100^\circ\text{C}$ ). While n-type doping using nitrogen gas which is supplied into the growth chamber by diffusion through the partly porous graphite crucible is uncritical, high p-type doping for a low substrate resistivity is rather difficult. In the case of p-type doping the concept of using doping gases like TMA (tri-methyl-aluminum) fails due to an untimely thermal dissociation prior the supply into the crucible. Therefore, aluminum is added as solid or solid compound to the SiC source material. Due to the high aluminum partial pressure a quick exhaustion and hence strong decrease of acceptor incorporation is observed during growth. We have recently developed a modified physical vapor transport (M-PVT) technique which uses an additional gas pipe for the supply of various doping gases into the SiC growth chamber. We already succeeded growing 4H- and 6H-SiC single crystals with a diameter of up to 40mm and with a defect density comparable to conventional PVT growth. For p-type doping we installed an external, heated, aluminum containing reservoir. A flux of inert carrier gas carried the aluminum gas species into the growth cell. Using this modified PVT growth setup the axial acceptor incorporation into the SiC crystal was improved significantly: An average hole concentration of  $p = 1 \times 10^{19} \text{ cm}^{-3}$  could be realized which varied only by a factor of 2 during one growth run. For comparison: Using the conventional configuration with aluminum as part of the SiC source material a variation of at least factor 10 was observed. In the case of 6H-SiC the substrate resistivity was as low as  $0.2 \text{ }\Omega\text{cm}$  which already meets the specifications for high power bipolar device applications. In the case of 4H-SiC the lowest resistivity up to now was  $6 \text{ }\Omega\text{cm}$ . However, it should be pointed out that this high value is due to the low doping level of  $p = 4 \times 10^{16} \text{ cm}^{-3}$  which was not yet pushed to the limit. The presentation will include a brief review of the technological implementation of the modified PVT setup. The main part will focus on p-type doping using aluminum. As an outlook we will present first results on n-type doping of SiC using the donor phosphor. The latter is of particular interest for fundamental studies of point defects in SiC. However, first results by Laube and Pensl indicate, that phosphor may also be of technological interest due to the expectation of a higher solubility limit in SiC than nitrogen.

10:40 AM

**U7, Semi-Insulating Bulk Single Crystals of 6H Silicon Carbide:** *A. Gupta*<sup>1</sup>; A. Giordana<sup>2</sup>; M. Yoganathan<sup>1</sup>; J. Whitlock<sup>2</sup>; A. Souzis<sup>1</sup>; I. Zwieback<sup>1</sup>; T. Anderson<sup>1</sup>; <sup>1</sup>II-VI, Inc., 20 Chapin Rd., Pine Brook, NJ 07058 USA; <sup>2</sup>Formerly with Northrop-Grumman, Morris Plains, NJ 07950 USA

Silicon Carbide (SiC) is a wide bandgap semiconductor useful for electronic devices operating in hostile environments. Specifically, high-power RF applications require semi-insulating (SI) SiC wafers with an electrical resistivity ( $\bar{n}$ ) above  $10^5 \text{ }\Omega\text{-cm}$  at  $300^\circ\text{C}$ . Although SiC is a wide band gap material, the presence of background shallow donors and acceptors like N (n-type), Al, and B (p-type), makes production of semi-insulating SiC substrates a challenge. Therefore, a higher purity source material, or a source with a compensating, deep trapping impurity (e.g. vanadium) becomes necessary in order to produce semi-insulating SiC. However, these dopants may negatively affect the carrier mobility and thermal conductivity. Therefore the ability to achieve semi-insulating properties without intentional doping is preferable. Semi-insulating bulk single crystals of 6H SiC, 50mm in diameter and larger, vanadium compensated and undoped, were grown using the conventional PVT technique and an advanced PVT technique (APVT). The latter incorporates in-situ synthesis of SiC source from high-purity silicon and carbon. Compared to PVT, APVT has demonstrated a factor of 10 reduction in B and Al impurity concentrations. Electrical properties of SiC wafers from PVT and APVT-grown 6H-SiC ingots were characterized using Hall effect measurements at various temperatures. The data for doped material grown by PVT, indicate an activation energy of about 1.4 eV which is consistent with V doping. For undoped material grown by APVT, the value of the activation energy is lower, typically between 0.4 and 1.1 eV. This indicates that intrinsic defects may be responsible for the conductivity of undoped 6H SiC. In some of the APVT-grown 6H-SiC crystals,  $\bar{n}$  measured at room temperature was on the order of  $10^7 \text{ }\Omega\text{-cm}$ , indicating that APVT may be a promising technique for the growth of semi-insulating SiC without vanadium compensation. We believe that even larger resistivities can be achieved with further improvement in the growth process purity. Detailed microscopic maps of micropipe density distributions, screw dislocation and total defect levels are made utilizing an automated in-house image recognition system. Wafers are also characterized by Raman microscopy, high resolution x-ray measurements and cross polarized UV imaging. This paper will outline the progress in production of SI 6H SiC at II-VI. We will present characterization results and discuss the effects of doping and source purity as related to the issues reviewed above.

11:00 AM

**U8, Comparative Characterization of Differently Oriented SiC Wafers:** *Peter G. Muzykov*<sup>1</sup>; Yuri I. Khlebnikov<sup>1</sup>; Igor I. Khlebnikov<sup>2</sup>; Robert T. Bondokov<sup>2</sup>; Alexander E. Grekov<sup>2</sup>; Serguei I. Maximenko<sup>2</sup>; Stanislav I. Soloviev<sup>2</sup>; Tangali S. Sudarshan<sup>2</sup>; <sup>1</sup>Bandgap Technologies, Inc., 1428 Taylor St., Columbia, SC 29201 USA; <sup>2</sup>University of South Carolina, Dept. of Electl. Eng., 301 S. Main St., Columbia, SC 29208 USA

The traditional and commonly used growth direction of SiC boules is along c-axis and commercially available SiC wafers are Si-face grown wafers. However superior SiC crystal properties for  $\{100\}$  and  $\{110\}$  planes (*p*- and *a*- faces) such as low density or even absence of micropipes, higher growth rate, polytype homogeneity, may result in significantly higher potential of *a*- and *p*-faces for crystal growth and device fabrication. The properties of SiC in  $\{100\}$  and  $\{110\}$  directions are not fully investigated. In this paper we report defect characterization of the Si (0001), *a*-, *p*- face SiC wafers and attempt to correlate electrical characteristics of Schottky diodes with structural quality of wafers and its orientation. *a*-, *p*- and Si-face oriented SiC wafers cut from the same boule, and as grown *a*-face wafer are used in the experiments. The Knoop hardness and surface roughness are measured after simultaneous wafer chemo-mechanical polishing. Resistivity and doping concentration of the wafers are evaluated by Hall, CV, and contactless resistivity measurements. A cross-reference defect analysis is carried out using EBIC, chemical etching in molten KOH, and stress mapping in the cross-polarized light. The micropipes, which appear as a bright "butterflies", and other structural defects are seen in the stress map of the Si-face samples, whereas no "butterflies" or black and white contrast have been observed for *a*- and *p*-face samples. A comparison between stress map, EBIC, and chemical etching as well as the results of electrical characterization will be presented.

11:20 AM

**U9, Modeling of In-Situ Off-Axis Seeding Surface Preparation Conditions for SiC PVT Growth:** Roman V. Drachev<sup>1</sup>; Dmitry I. Cherednichenko<sup>1</sup>; Igor I. Khlebnikov<sup>1</sup>; Tangali S. Sudarshan<sup>1</sup>; <sup>1</sup>University of South Carolina, Electl. Eng., 301 S. Main St., Columbia, SC 29208 USA

The structural quality of epi- and bulk PVT grown SiC can be significantly improved by means of low off-axis angle ( $\approx 8^\circ$ ) seeding substrates, which surface has to be treated to remove the damaged layer and reveal its vicinal structure. This is typically done by in-situ substrate thermal etching, which conditions (temperature, argon pressure and duration) must be optimized so as to get the desired step height and avoid severe surface graphitization (accumulation of residual carbon). However, the experimental study of the preparation conditions is expensive and, sometimes, inefficient. Hence an analytical investigation is reasonable to undertake that is reported here. If the seeding surface intersects the equilibrium small index crystal face at some angle, this can be considered as a distributed surface defect. According to the anisotropy of SiC free surface energy the minimum of surface area and minimum of free surface energy are not realized simultaneously and, therefore, the initially flat substrate surface would differ from its equilibrium shape. This is why under given etching conditions, the seeding surface begins breaking up into step systems (facets) if any molecular mechanism is able to reconstruct the surface during the time of the process. It can be shown that for the evaporation-condensation mechanism when the solid surface is in contact with an ambient gas, the correlation between the normal to surface and lateral velocities of faceting is:  $dx_y/dt = -(dy_y/dt)/\tan\alpha$ . Then the amount of material removed per one facet can be estimated as:  $G(t) = \bar{n} \cdot \bar{v} \cdot (A \cdot t)^{1/3} / \bar{A}^{2/3}$ , where  $A = C_o \cdot \bar{v} \cdot \bar{U}^2 \cdot D_G / k \cdot T$ ,  $\bar{n}$ - SiC bulk density,  $C_o(T)$ - equilibrium concentration of SiC vapor species at temperature T,  $\bar{v}$ - (0001) SiC face surface energy,  $\bar{U}$ - the molecular volume,  $D_G$ - SiC diffusivity in argon, t- time of etching, k-Boltzmann constant,  $\bar{A}^{2/3}$ - Gamma function and  $\bar{v}$  is the geometrical parameter determined by the off-axis angle  $\alpha$ . The residual carbon surface density can be expressed as:  $G_{CR}(t) = G(t) \cdot \bar{a}(T)$  (where  $\bar{a}(T) = 1 - 1/\zeta(T)$  stands for the effectiveness of SiC sublimation and  $\zeta(T)$ - stoichiometry coefficient of SiC vapor). The estimations are in good ( $\pm 10\%$  for  $3^\circ \leq \alpha \leq 6^\circ$ ) agreement with the experimental results reported. As is clear from the plots in Fig.1, the number of carbon atomic layers  $N_{CR}$  that would reside at the seeding surface by the end of etching drastically reduces with decrease of the off-axis angle. At the same time, moderate etching temperature ( $\approx 2000^\circ\text{C}$ ) and elevated argon pressure ( $\sim 150$  Torr) would also repress the seeding surface graphitization during the in-situ preparation.

11:40 AM

U10, Late News

## Session V: Nitride Doping and Defects

Thursday PM Room: Lotte Lehmann  
June 27, 2002 Location: University of California

*Session Chairs:* Len Brillson, The Ohio State University, 205 Dreese Lab., 2015 Neil Ave., Columbus, OH 43210-1272 USA; Steve Ringel, The Ohio State University, 205 Dreese Lab., 2015 Neil Ave., Columbus, OH 43210-1272 USA

1:20 PM Student

**V1, Growth and Impurity Incorporation in InGaN Grown by RF-Plasma Assisted Molecular Beam Epitaxy (MBE):** Christiane Poblenz<sup>1</sup>; J. S. Speck<sup>1</sup>; <sup>1</sup>University of California-Santa Barbara, Matls. Eng. Dept., Santa Barbara, CA 93106 USA

InGaN alloys have been predicted to be useful in electronic device applications such as high electron mobility transistor (HEMT) structures due to the lower electron effective mass in InGaN as compared to GaN. Transport studies on such structures have been limited, however, by a high background carrier concentration in the InGaN channel. While this has not been reported experimentally with regard to HEMTs or in bulk  $\text{In}_x\text{Ga}_{(1-x)}\text{N}$  alloys grown by MBE, it has been predicted by Stampfl *et al.*

that O and Si impurities (which both act as donors) will readily incorporate during growth of InN. We present a set of experiments which explicitly study impurity incorporation in InGaN alloys grown by RF-plasma assisted MBE and relate this to measured transport properties InGaN-based structures. The  $\text{In}_{0.17}\text{Ga}_{0.83}\text{N}$  layers under study were all grown In-rich in the In-droplet growth regime. A growth diagram for MBE-InGaN has been developed and will be presented. The diagram is consistent with that developed for MBE-GaN, but with build-up of an In wetting layer instead of a Ga wetting layer. Secondary ion mass spectroscopy (SIMS) was used to investigate the impurity incorporation in several structures, two of which are shown in Figure 1. Each contain an In-rich  $\text{In}_{0.17}\text{Ga}_{0.83}\text{N}$  layer grown at  $600^\circ\text{C}$  placed between two Ga-rich GaN layers grown at  $750^\circ\text{C}$  and  $600^\circ\text{C}$ . Growth of the structure shown in Figure 1(a) was continuous, whereas a desorption step was performed at the interface indicated in Figure 1(b) to desorb excess indium. The SIMS profiles reveal a factor of 3 increase in both oxygen and boron in  $\text{In}_{0.17}\text{Ga}_{0.83}\text{N}$  as compared to GaN at  $600^\circ\text{C}$ . In addition, the oxygen profile tapers down in the growth direction from InGaN to GaN in Figure 1(a) but is abrupt in Figure 1(b) as a result of the desorption step. In contrast, the boron profile is abrupt in both cases. We relate this increase in impurity incorporation and behavior of the SIMS profiles to the different structures of the Ga and In wetting layers. The structure of the Ga wetting layer has been shown to be a stable fluid-like bilayer above a Ga-terminated GaN(0001) crystal under Ga-rich conditions. The In wetting layer under In-rich conditions has been investigated by Chen *et al.* and found to be a single monolayer above an InGaN(0001) surface. This study demonstrates the profound impact of surface atomic structure on impurity incorporation and the protective nature of the Ga wetting layer as compared to the In wetting layer. Carrier concentrations in bulk InGaN have also been measured and are on the order of  $10^{18}\text{cm}^{-3}$ , consistent with high levels of unintentional dopants. In order to control material properties, and ultimately device characteristics this understanding of impurity incorporation in InGaN is essential.

1:40 PM Student

**V2, Si Doping of High Al Mole Fraction  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  Alloys with RF Plasma MBE:** Jeonghyun Hwang<sup>1</sup>; William J. Schaff<sup>1</sup>; Lester F. Eastman<sup>1</sup>; Shawn T. Bradley<sup>2</sup>; Leonard J. Brillson<sup>2</sup>; <sup>1</sup>Cornell University, Electl. & Compu. Eng., 429 Phillips Hall, Ithaca, NY 14850 USA; <sup>2</sup>Ohio State University, Electl. Eng., 205 Dreese Labs., Columbus, OH 43210 USA

Among the group III nitrides, the  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  alloys are especially important for the semiconductor devices such as light emitting diodes or lasers in the blue and UV range, UV detectors, and high-power/high-temperature transistors. Successful doping of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  alloys is essential for the realization of such applications, but  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  alloys are known to suffer a rapid decrease in the conductivity with increasing Al mole fraction. Here we report that very high levels of n-type doping concentration in  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  alloys were recently achieved using RF plasma induced Molecular Beam Epitaxy and Si as a dopant. For the n-AlGa<sub>x</sub>N with 65% Al mole fraction,  $1 \times 10^{20}\text{cm}^{-3}$  electron concentrations have been obtained with a room temperature hall mobility of  $23\text{cm}^2/\text{Vsec}$ . For a fixed Si doping flux, CV measurement showed that electron density fell from  $1 \times 10^{19}$  to  $5 \times 10^{18}\text{cm}^{-3}$  with increasing Al mole fraction from X=0 to X=0.5, which indicated donor levels was becoming deep with increasing Al content. Electron density measured by Hall measurement fell more quickly, however the electron density is higher than expected for what would presumably be deep donor ionization energy for materials with such large bandgaps. With increased Si fluxes, we could get higher electron density, up to  $1 \times 10^{20}\text{cm}^{-3}$ , when X=0.65. Further improvement is likely to occur in the future. Temperature variable Hall measurement showed no variation in electron density with temperature and CL measurement showed strong luminescence at the band edge. Detailed growth conditions and their effects on high conductivity high Al mole fraction AlGa<sub>x</sub>N will be discussed in the presentation. Crystal quality and surface morphology of Si doped  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  measured by XRD and AFM as a function of Al mole fraction will be also included.

2:00 PM

**V3, More Efficient P-Doping for GaN?:** An-Ban Chen<sup>1</sup>; <sup>1</sup>Auburn University, Physics Dept., 206 Allison Lab., Auburn, AL 36849-5311 USA

The p-type doping is still a serious problem for GaN for optimum device performance. Mg is the dopant commonly used for the p-type nitride materials. However, the activation efficiency of Mg is still very small, in the 1 to 2% range. The main reason is that the ionization energy

for Mg in GaN is quite large. The first step to improve the p-doping efficiency is to find acceptors with small ionization energies. Recently, we have obtained a set of acceptor ionization energies in GaN. Our results showed that only two acceptors, C and Be, have smaller acceptor ionization energies (152 and 187 meV respectively) than Mg (224 meV). However, formation-energy calculations showed that Be is energetically more favorable to be an interstitial rather than a substitutional impurity. If this result holds, Be will not be a viable dopant, leaving C as the leading candidate to compete with Mg for more efficient p-doping in GaN. Even though C is an amphoteric impurity, the acceptor behavior is still favored under a favorable growth condition. While much more detailed studies are needed to establish the doping and activation processes, we want to assess the doping efficiency of C in GaN as compared to Mg. Since the current solubility theory is still not accurate enough to predict impurity incorporation in the non-equilibrium doping processes (epitaxial growth and ion implantation) in GaN, the present work focused on evaluating the efficiency of free-hole generation for a given acceptor concentration  $n_A$ . We carried out a self-consistent calculation that not only treats the interdependence among carrier concentration, ionization probability, the fermi energy, and the ionization energy, but also includes the variation of ionization energy with the carrier concentration. Here we summarize the important results. First the acceptor ionization energy was found to be very sensitive to the free hole screening. For example, with  $10^{18} \text{ cm}^{-3}$  free holes, the screened ionization energy of C in GaN was found to be 110 meV at the room temperature, as compared to the unscreened value of 152 meV. We also found that the relatively large ionization energy alone (224 meV) can account for the poor activation efficiency (1 to 2%) of Mg in GaN seen in the experiments. The efficiency tends to drop as the acceptor concentration  $n_A$  increases. With  $n_A = 2 \times 10^{19} \text{ cm}^{-3}$ , a moderate compensating donor concentration  $n_D = 10^{17} \text{ cm}^{-3}$  can pull the activation efficiency of Mg below 1%, while the corresponding efficiency for C still remains at 6%. The reason that C is more efficient is due to its smaller ionization energy and a further reduction by the free-hole screening. Based on our calculation, C can achieve  $1.3 \times 10^{18} \text{ cm}^{-3}$  free holes GaN with a doping concentration  $n_A = 2 \times 10^{19} \text{ cm}^{-3}$  and a modest level of compensation, while Mg can only generate  $1.5 \times 10^{17} \text{ cm}^{-3}$  free holes. In conclusion, the present study showed that C has a potential to be a more efficient p-type dopant than Mg for GaN. These results should encourage more research efforts to study this doping technology.

#### 2:20 PM

**V4, Effect of Electron Irradiation on Growth and Properties of GaN Grown by RF Plasma Molecular Beam Epitaxy:** *Dimitris Korakakis*<sup>1</sup>; Huicheng Guo<sup>1</sup>; Luke J. Holbert<sup>1</sup>; Ting Liu<sup>1</sup>; Craig H. Swartz<sup>1</sup>; Aaron J. Ptak<sup>1</sup>; Lijun Wang<sup>1</sup>; Nancy C. Giles<sup>1</sup>; Thomas H. Myers<sup>1</sup>; <sup>1</sup>West Virginia University, Physics, PO Box 6315, Morgantown, WV 26506 USA

Reflection high-energy electron diffraction (RHEED) is one of the most useful and undoubtedly the most widespread of the various techniques used for in-situ monitoring during molecular beam epitaxy growth. While it was recognized early that RHEED could affect growing material, it has proven to be fairly benign for growth of GaAs and related III-V materials. We have recently observed that RHEED can have a dramatic effect on the incorporation of impurities/generation of point defects in GaN and InN. The effect of electron irradiation during the growth of III-nitrides can be visually observed by a "stripe" associated with the RHEED beam position. Further analysis, using a high-energy electron gun capable of irradiating large sample areas, reveals significant differences in the properties of the grown materials. While there is no pronounced decrease in the growth rate due to the presence of electron irradiation; there are cases where a variation of the order of 5% is observed. However, electron irradiation during growth can have a dramatic effect on the incorporation of impurities. Reductions in carbon and oxygen concentration by over an order of magnitude are observed with electron irradiation, as determined by secondary ion mass spectroscopy (SIMS). Furthermore, there is evidence suggesting that high-energy electron irradiation such as occurs during RHEED has a dramatic effect on reducing surface segregation of dopants. Photoluminescence, Raman, UV-fluorescence microscopy and atomic force microscopy results indicating improved material quality and possible models explaining our results will also be presented. The work at WVU was supported by ONR Grant N00014-96-1-1008 and ONR Grant N00014-99-1-0520, both monitored by Colin E.C. Wood.

#### 2:40 PM

**V5, Defects Introduced in GaN/AlGaIn HEMT Structures from SiC Substrate Defects:** *B. D. Poust*<sup>1</sup>; T. S. Koga<sup>1</sup>; M. S. Goorsky<sup>1</sup>; R. Sandhu<sup>1</sup>; R. Hsing<sup>2</sup>; M. Wojtowicz<sup>2</sup>; A. Khan<sup>3</sup>; <sup>1</sup>University of California, Dept. of Matls. Sci. & Eng., Los Angeles, CA 90095 USA; <sup>2</sup>TRW, Elect. Tech. Div., Space & Elect. Grp., Redondo Beach, CA 90278 USA; <sup>3</sup>University of South Carolina, Dept. of Electl. Eng., 301 S. Main St., Columbia, SC 29208 USA

This study addressed how defects in SiC substrates influenced the crystallographic properties of GaN/AlGaIn high electron mobility structures layers deposited by metalorganic vapor phase epitaxy. This study is part of a larger effort to relate substrate defects to device performance in III-nitride structures grown on high resistivity SiC structures. We employed double crystal reflection x-ray topography and both symmetric (0008) and asymmetric reflections to image dislocations, micropipes, and low angle boundaries in SiC substrates. The low angle boundaries were tilted by » tens-hundreds of arcseconds, and the micropipe defects exhibited both tilt and strain with respect to the surrounding matrix. The strain around the micropipe defects is on the order of  $10^{-5}$  and the tilt of the micropipe diffracting region can be as great as 10s of arcsec. After deposition of the HEMT AlGaIn and GaN layers, x-ray topography images were generated from the substrate and from the GaN buffer layer [(0004) symmetric reflection]. The defects in the substrates were not measurably changed after the epitaxial layer deposition, but the wafers did exhibit more curvature, as would be expected from the stress introduced by the slightly mismatched nitride layers. Even though the GaN layer peak possessed a much greater full width at half maximum (» 200 arcsec) than the SiC substrate peak (» 20 arcsec), the micropipes and tilt boundaries from the SiC substrate produced structural defects in the GaN layers as did other defects such as inclusions. A clear one-to-one correlation between SiC substrate defects and GaN defects exists. There was also evidence that—in a few cases—crystallographic defects in the epitaxial film did not originate with substrate defects.

#### 3:00 PM Break

#### 3:20 PM

**V6, Heterogeneous Integration of Low Dislocation Density III-Nitride Epitaxial Material on Silicon-On-Insulator (SOI) Substrates:** *Joseph E. Van Nostrand*<sup>1</sup>; John Boeckl<sup>1</sup>; James E. Ehret<sup>1</sup>; <sup>1</sup>Air Force Research Laboratory, Matls. & Mfg. Direct., 2241 Avionics Cir., Bldg. 620, WPAFB, OH 45433-7322 USA

The advanced digital and analog circuit industry is replete with Si and SiGe components on silicon-on-insulator (SOI) substrates. A small number of groups have previously explored deposition of GaN by MOCVD on SOI substrates for two primary advantages: 1) to exploit compatibility with the leading commercial semiconductor technology, and 2) to explore the use of the thin silicon layer on silicon dioxide as a "compliant" substrate. Unfortunately, this has been met with limited success in that GaN of a quality comparable to GaN grown on sapphire could not be achieved routinely over a large area, if at all. In our efforts to understand the growth of GaN on the Si face of SiC and on silicon substrates, we have encountered a large degree of success in comparison to literature results. We have employed our understanding of materials issues, as well as the outstanding degree of in-situ diagnostics and control afforded by the molecular beam epitaxy technique to obtain GaN on SOI silicon of remarkably good microstructure and morphology. In this work, we demonstrate a GaN on SOI technology that shows great promise for use in heterogeneous integration of III-nitride heteroepitaxial device layers with SOI substrates that could subsequently be integrated into CMOS fabrication lines. Cross-sectional transmission electron microscopy (XTEM) shows the as grown GaN on SOI substrates to have  $\sim 5 \times 10^7 \text{ cm}^{-2}$  dislocations near the surface of a 1  $\mu\text{m}$  thick film. Further, and somewhat surprisingly, the GaN is found by XTEM to be completely cubic, with no wurtzite phases present. Low temperature (4K) high-resolution photoluminescence measurement shows a single, strong emission peak at 3.4504 eV, with a FWHM of 19 meV, and very little "yellow band." Finally, electrical transport (Hall) measurements are found to be dominated by the carriers in the silicon, suggesting (based on depletion width) a free carrier population  $< 10^{17} \text{ cm}^{-3}$  in the nitride epitaxial film. These III-Nitride epitaxial thin film results show great promise towards use in a commercial technology with the high-speed/high-power advantages of nitride materials as well as the mature, low-noise/low-power technology of CMOS.

3:40 PM

**V7, Reverse-Bias Leakage Current Reduction in GaN Schottky Diodes by Surface Modification with an Atomic Force Microscope:** *Eric J. Miller<sup>1</sup>*; Daniel M. Schaadt<sup>1</sup>; Christopher W. McKinney<sup>1</sup>; Edward T. Yu<sup>1</sup>; Patrick Waltereit<sup>2</sup>; Christiane Poblenz<sup>2</sup>; James S. Speck<sup>2</sup>; <sup>1</sup>University of California–San Diego, Dept. of Electl. & Compu. Eng., La Jolla, CA 92093-0407 USA; <sup>2</sup>University of California–Santa Barbara, Matls. Dept., Santa Barbara, CA 93106 USA

Minimizing the reverse-bias leakage current in GaN-based electronic devices is crucial for their integration into low-noise and low-power circuit applications. The high concentration of threading dislocations typical of Group III-Nitride alloys grown by molecular beam epitaxy (MBE) has been shown to be responsible for the majority of the leakage current in Schottky diodes fabricated on MBE-grown GaN. Recently, we have demonstrated that an atomic-force microscope (AFM) modified to allow measurement of local current-voltage characteristics can be used to block the dislocation-related leakage paths by applying a bias between the AFM tip and sample and growing a thin insulating layer in the vicinity of the leakage path. In the current investigation, we utilized this technique to modify large-areas of the GaN surface (20  $\mu\text{m}$  x 20  $\mu\text{m}$ ) to block the dislocation-related leakage paths in the area. Schottky diodes were fabricated on these and unmodified areas, and the current-voltage characteristics of the diodes were compared. The reverse-bias leakage currents in the modified-surface diodes were reduced by one to four orders of magnitude compared to unmodified-surface diodes, thus demonstrating the importance of blocking the dislocation-related leakage current paths in devices where low off-state leakage current is essential. This suggests that other surface treatments based on a similar physical process could significantly reduce the reverse-bias leakage currents in Schottky diodes fabricated from MBE-grown material.

4:00 PM Student

**V8, High Energy Proton Irradiation of MgO/GaN Metal Oxide Semiconductor Diodes:** *Jihyun Kim<sup>1</sup>*; B. P. Gila<sup>2</sup>; R. Mehandru<sup>1</sup>; Ben Luo<sup>1</sup>; A. H. Onstine<sup>2</sup>; Fan Ren<sup>1</sup>; Cammy R. Abernathy<sup>2</sup>; R. Dwivedi<sup>3</sup>; K. K. Allums<sup>2</sup>; T. N. Forgarty<sup>3</sup>; R. Wilkins<sup>3</sup>; Y. Irokawa<sup>1</sup>; Stephen J. Pearton<sup>2</sup>; <sup>1</sup>University of Florida, Cheml. Eng., Rm. 122, Cheml. Eng. Bldg., Gainesville, FL 32611 USA; <sup>2</sup>University of Florida, Matl. Sci., Gainesville, FL 32611 USA; <sup>3</sup>Prairie View A&M University, Ctr. for Appl. Radiation Rsrch., Prairie View, TX 77446 USA

There is increasing interest in development of GaN-based metal-oxide semiconductor field effect transistors(MOSFETs) and metal-insulator field effect transistor(MESFET) as high power switching devices. These have potential advantages over metal-semiconductor FETs in terms of reduced gate leakage current, high breakdown voltage and small switching losses. Numerous reports have appeared on the use of AlN, SiO<sub>2</sub>, SiN<sub>x</sub>, SiO<sub>2</sub>/Ga<sub>2</sub>O<sub>3</sub> and Ga<sub>2</sub>O<sub>3</sub>/Gd<sub>2</sub>O<sub>3</sub> insulators for GaN, with very promising results. An unambiguous demonstration of inversion behavior has not yet been achieved in these systems due to a number of factors. MgO is an alternative candidate as a gate dielectric for GaN because of its large bandgap(8eV) and smaller lattice mismatch for GaN(~6.5%) compared to Gd<sub>2</sub>O<sub>3</sub>(~20% mismatch). Some of the applications for GaN MESFET devices would be in satellite communication systems for weather forecasting or broad-band data transmission. It is necessary to understand the ability of the devices to withstand high fluxes of incoming radiation, particularly protons. In this talk, we report on the effect of 40MeV proton doses corresponding to more than 10 years in low earth orbit on the dc performance of MgO/GaN MOS devices. The forward turn-on voltage(VF) was found to decrease upon proton irradiation, but with little change in interface state density(Dit). Subsequent annealing at 500°C in H<sub>2</sub> lowered Dit in both irradiated and unirradiated devices. GaN metal oxide semiconductor diodes were demonstrated utilizing MgO as the gate oxide. MgO was grown via GSMBE at 100°C on MOCVD n-GaN buffers using a Mg elemental source and an electron cyclotron resonance oxygen plasma. H<sub>3</sub>PO<sub>4</sub> based wet-chemical etchant was used to remove MgO to expose the underlying n-GaN for ohmic metal deposition. Electron beam deposited Ti/Al/Pt/Au and Pt/Au were utilized as ohmic and gate metallization, respectively. After processing and testing, the MgO (100nm)/GaN diodes were exposed to proton irradiation at a dose of 5E9 cm<sup>-2</sup> and an energy of 40MeV. With optimized growth of MgO on GaN, interface state density of 2E11 cm<sup>-2</sup> and a breakdown field of 2-4 MV/cm with AC conductance measurement were obtained. After irradiation, both interface state density and forward breakdown voltage

were degraded. There was no change of diode I-V and C-V characteristics after a post-irradiation anneal at 300°C. However, with a 500°C for 2 minutes in forming gas, the irradiation damage was removed for the irradiated sample with metal contact deposited before the irradiation.

4:20 PM

V9, Late News

4:40 PM

V10, Late News

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**Session W:**

**Organic and Amorphous**

**Semiconductors: Materials and Devices**

Thursday PM

Room: MultiCultural Theatre

June 27, 2002

Location: University of California

*Session Chairs:* David Gundlach, IBM Zurich Research Laboratory, Säumerstrasse 4, CH-8803 Rüschlikon, Switzerland; Thomas Jackson, Pennsylvania State University, Dept. of Electl. Eng., University Park, PA 16802 USA

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1:20 PM

**W1, Jet-Printed Fabrication of Amorphous Silicon Thin-Film Transistors and Arrays:** *William S. Wong<sup>1</sup>*; Steven E. Ready<sup>1</sup>; Jeng P. Lu<sup>1</sup>; Jackson Ho<sup>1</sup>; Robert A. Street<sup>1</sup>; <sup>1</sup>Palo Alto Research Center, Elect. Matls. Lab., 3333 Coyote Hill Rd., Palo Alto, CA 94304 USA

The fabrication of large-area thin-film transistor (TFT) arrays is prohibitively expensive due in large part to the high number of photolithographically-based processing steps. By simplifying this process, the cost and complexity of fabricating TFTs for large-area applications such as flat-panel displays or imager arrays would be reduced. One approach to simplification is by using direct-writing methods to replace conventional photolithography. Direct-write technologies for materials processing presents opportunities to enhance conventional large-area electronic device fabrication. However, applications to matrix-addressed arrays require minimum feature sizes no greater than 20-30  $\mu\text{m}$  and similar layer-to-layer registration, which has so far proved difficult to achieve. Jet printing is an ideal technology for implementing the direct writing of etch masks due to its spatial control. Jet printing a phase-change material slightly above its solid/liquid phase transition temperature provides additional management over feature size. The printed phase-change material depends more on the cooling rate and less on the materials wetting properties since a frozen droplet cannot spread. In this situation, the substrate temperature controls the printed feature size for materials having excellent wetting properties. We will discuss the critical parameters affecting feature size and printed wax-mask resolution in which features below 25  $\mu\text{m}$  have been achieved on films of a-Si:H, a-Si<sub>3</sub>N<sub>4</sub> and metals using a combination of small drop volume and a phase-change wax media. Based on this methodology, we have fabricated a-Si:H thin-film transistors (TFTs) processed using printed wax masks in place of conventional lithography. Bottom-gate TFTs with source-drain contacts overlapping the channel were created using a four-mask process. The TFTs have I-V characteristics comparable to photolithographically patterned devices, with mobility of 0.6-0.9 cm<sup>2</sup>/V·s, threshold voltage of 2-3 V, and on/off ratios exceeding 10<sup>7</sup>, for devices with channel lengths below 50  $\mu\text{m}$ . Layer registration accuracy of better than 20  $\mu\text{m}$  was also achieved over print areas of about 5x5cm<sup>2</sup>. In addition, the printed wax-mask process has also been implemented in fabricating self-aligned TFT structures having laser-recrystallized polysilicon source/drain regions. TFT structures fabricated using the self-aligned process yielded devices with gate lengths as short as 40  $\mu\text{m}$  with no overlap constraint on the source and drain alignment over the a-Si:H channel region. These devices possessed threshold voltages ~ 3-4 V, on/off ratios of 10<sup>7</sup> with field effect mobility of ~ 0.6 cm<sup>2</sup>/V·s. Having established a small feature size printed-TFT process, the design and implementation of fabricating large-area active-matrix pixel arrays will also be presented. Figure 1 shows an optical micrograph of the superimposed wax-mask layers used to fabricate an array of transistors, having a pixel size of ~300  $\mu\text{m}$ .

THURSDAY PM

## 1:40 PM Student

### W2, Phosphorescent OLED Amorphous Silicon TFT Active-Matrix

**Pixel:** Jonathan Nichols<sup>1</sup>; Tom Jackson<sup>1</sup>; Mike Lu<sup>2</sup>; Mike Hack<sup>2</sup>; <sup>1</sup>Pennsylvania State University, Dept. of Electl. Eng., 121 EE E., University Park, PA 16802 USA; <sup>2</sup>Universal Display Corporation, 375 Phillips Blvd., Ewing, NJ 08618 USA

For high information content organic light emitting diode (OLED) displays active-matrix pixel addressing can provide improved display performance and reduced power consumption. The high-efficiency of phosphorescent OLEDs allows low performance thin film transistors (TFTs), such as those based on hydrogenated amorphous silicon (a-Si:H) or even organic semiconductors, to be used as OLED drive devices. The low processing temperatures of a-Si:H or organic TFTs allows reduced cost manufacturing and also the potential for display fabrication on flexible polymeric substrates. We have fabricated two-transistor amorphous silicon (a-Si:H) TFT active-matrix OLED pixels using high-efficiency small molecule phosphorescent OLEDs. An a-Si:H TFT active-matrix OLED pixel was reported previously using polymeric OLED material, however, the relatively low-efficiency of the fluorescent material required the use of large drive voltages ( $V_{\text{OLED}} = -10$  V,  $V_{\text{DD}} = 25$  V, and  $V_{\text{DATA}} = V_{\text{SELECT}} = 30$  V for 100 cd/m<sup>2</sup>, giving a  $V_{\text{GS}}$  for the drive transistor near 30 V) for the OLED and pixel transistors. Large drive voltages are undesirable for a-Si:H TFTs since they can cause device instability and related display non-uniformity; high-efficiency phosphorescent OLEDs allow substantially reduced drive voltages. The two-transistor OLED pixel and schematic are shown in Fig. 1 and the pixel cross-section is shown in Fig. 2. The a-Si:H TFTs had a field-effect mobility of  $\sim 1$  cm<sup>2</sup>/V-s, threshold voltage of  $\sim 2$  V, on/off current ratio  $>10^7$ , and a subthreshold slope of  $\sim 0.4$  V/decade. The I-V characteristics for the OLED pixel are shown in Fig. 3. Using a drive transistor with W/L ratio of 8.5 ( $W = 170$   $\mu\text{m}$ ,  $L = 20$   $\mu\text{m}$ ) an OLED current of approximately 1.8  $\mu\text{A}$  ( $\sim 3.1$  mA/cm<sup>2</sup>), corresponding to a brightness of more than 400 cd/m<sup>2</sup> (using 24 cd/A for the OLED luminance efficiency and averaged over the total pixel area), was obtained at  $V_{\text{DD}} = V_{\text{DATA}} = V_{\text{SELECT}} = 20$  V. Using a diode drive voltage of 10 V the current required for a brightness of 100 cd/m<sup>2</sup> is obtained for a data voltage less than 15 V. The data voltage is the sum of the OLED voltage and the required drive transistor gate-source voltage ( $V_{\text{GS}}$ ) and  $V_{\text{GS}}$  for the drive transistor is less than 8 V at 100 cd/m<sup>2</sup> and less than 12 V for 400 cd/m<sup>2</sup>. Such low drive voltages allow good TFT stability and display uniformity for low-cost a-Si:H backplane OLED displays.

## 2:00 PM Student

### W3, Development of New Blue Light Emitting Material and its Device

**Characteristics:** Seungmoon Pyo<sup>1</sup>; Shun-Chi Chang<sup>1</sup>; Qibing Pei<sup>2</sup>; Yang Yang<sup>1</sup>; <sup>1</sup>University of California-Los Angeles, MSE, 405 Hilgard Ave., Los Angeles, CA 90095 USA; <sup>2</sup>SRI International, 333 Ravenswood Ave., Menlo Park, CA 94025 USA

The development of blue light emitting polymer is of particular importance in the field of polymer light emitting diodes (PLEDs). A number of blue light-emitting polymers have been designed and synthesized to obtain high efficient photoluminescence (PL) and electroluminescence (EL). However, due to their intrinsic properties such as aggregate formation upon bias and/or excimer formation, only a few are promising for the fabrication of efficient blue light emitting diodes. In this presentation, new thermally stable and highly efficient blue-emitting polymers will be reported. In addition, highly efficient blue PLEDs will also be discussed.

## 2:20 PM

### W4, Energy Transfer and Triplet Exciton Confinement in Phosphorescent Polymer Light-Emitting Diodes:

**Fang-Chung Chen<sup>1</sup>; Shun-Chi Chang<sup>1</sup>; Yang Yang<sup>1</sup>; Mark E. Thompson<sup>2</sup>; <sup>1</sup>University of California-Los Angeles, Dept. of Matls. Sci. & Eng., Los Angeles, CA 90095-1595 USA; <sup>2</sup>University of Southern California, Dept. of Chem., L. J. Stabler Lab., Los Angeles, CA 90089 USA**

Due to the harvest of both singlet and triplet states, high-efficiency has been achieved in polymer light-emitting diodes (PLEDs) by doping with phosphorescent dyes. In this presentation, two fluorescence host materials, poly(vinylcarbazole) and poly(9,9-bis(octyl)-fluorene-2,7-diyl), and five phosphorescent metal complex dopants were investigated. It is found that the device performance is closely related to the relative position of the triplet energy levels of host and dopant materials. The energy transfer efficiency and the confinement of excitons (in both

k-space and time domain) play important roles determining the device efficiency. The details of the exciton energy transfer and device operation mechanism will be discussed.

## 2:40 PM

### W5, Blue Luminescence from Thin Films of Tris(8-Hydroxyquinoline)

**Aluminium(III): Michele Muccini<sup>1</sup>; Kester Kenevey<sup>1</sup>; Henrik Hansen<sup>1</sup>; Giampiero Ruani<sup>1</sup>; Roberto Zamboni<sup>1</sup>; Norberto Masciocchi<sup>2</sup>; Angelo Sironi<sup>3</sup>; <sup>1</sup>Istituto per lo Studio dei Materiali Nanostrutturati, ISMN-CNR, ISMN, via P. Gobetti, 101, Bologna I-40129 Italy; <sup>2</sup>Università dell'Insubria, Dep. Scienze Chimiche, Fisiche e Matematiche, via Lucini, 3, Como 22100 Italy; <sup>3</sup>Università di Milano, Dept. Chimica Strutturale e Stereochimica Inorganica, via Venezian, 21, Milano 20133 Italy**

Tris(8-hydroxyquinoline) aluminium(III) (Alq<sub>3</sub>) and its derivatives are to date among the most widely used compounds for organic optoelectronic devices such as LEDs, and large area displays. Alq<sub>3</sub> may be used as emitting layer or as hole transport layer in multilayer device structures. In both cases the control of the molecular packing in the film is crucial as it determines the electronic structure of the material and thus its charge transport and optical emission properties. Recently, Alq<sub>3</sub> has been demonstrated to be polymorphic and the alpha, beta and delta phases have been isolated and characterized [JACS, JCP]. The correlation between the molecular packing and the optical properties of a-Alq<sub>3</sub> and b-Alq<sub>3</sub> showed that the photophysics of the material is determined by the intermolecular quinoline-quinoline interactions. Luminescence of polycrystalline powder d-Alq<sub>3</sub> has been reported to be blue shifted with respect to the typical green luminescence of a-Alq<sub>3</sub> and b-Alq<sub>3</sub> [JCP]. However, Alq<sub>3</sub> thin films grown either by vacuum sublimation or by solution processing invariably showed the typical green emission. Here we report the first blue emitting Alq<sub>3</sub> thin films obtained both by vacuum sublimation and by solution processing. We correlate the optical and vibrational properties to the molecular packing obtained by X-ray diffraction and discuss the eventual presence and role of the two Alq<sub>3</sub> isomers. We further discuss the implications for the development of OLED devices based on Alq<sub>3</sub> where the optoelectronic properties are controlled by the molecular packing. The availability of green and blue emitting Alq<sub>3</sub> and their eventual combination in the same device may be of interest for organic full-colour displays.

## 3:00 PM Break

## 3:20 PM Student

### W6, Morphology and Impurity Effects in Pentacene Thin-Film Transistors:

**Stijn Verlaak<sup>1</sup>; Dimitri Janssen<sup>1</sup>; Barundeb Dutta<sup>1</sup>; Paul Heremans<sup>1</sup>; <sup>1</sup>IMEC, MCP/OE, Kapeldreef 75, Leuven 3001 Belgium**

Organic thin-film transistors (OTFT) are promising devices for low-cost large-area electronic applications. Nowadays, pentacene is amongst the most popular oligomer semiconductors for use in OTFT's. We used purified pentacene grown on thermally oxidized silicon wafers with a backside gate contact and shadow-mask evaporated Au top contacts to make OTFT's. The substrate was kept at room temperature, while deposition fluxes varied between 0,01 and 0,45 Å/s. By applying different substrate cleanings, it is possible to vary the surface energy and therefore the growth. Substrates cleaned with acetone and isopropylalcohol had a contact angle of 26,5°. Pentacene grown on those surfaces formed dendritic grains approximately 5  $\mu\text{m}$  in size. Pentacene grown on surfaces which were in addition cleaned with an oxygen-plasma (contact angle 14,5°), formed compact grains  $\sim 0.5$ -1  $\mu\text{m}$  in size. Hole mobilities in the latter film were of order 1E-3 to 1E-2 cm<sup>2</sup>/Vs, while the mobilities in the film with dendritic grains were around 1E-1 to 1E+0 cm<sup>2</sup>/Vs. The difference in mobility is attributed to grain boundary effects which are more pronounced in films with compact grains. It is interesting to compare those results with films grown using as-received pentacene. Different films were grown with varying flux and substrate temperature. Due to the substrate cleaning applied, only the compact grain morphology was observed. The films show a definite trend towards higher mobility with increasing positive threshold voltage. Even for these films with compact grains, mobilities as high as 1E-1 to 1E+0 cm<sup>2</sup>/Vs were readily obtained, albeit with impractically high threshold voltages. We tentatively explain the results by assuming that deposition conditions with lower pentacene supersaturation favour higher concentrations of dopant impurities to become incorporated in the pentacene film. More dopant impurities not only lead to higher threshold voltages, but also provide sufficient free carrier densities to mask grain boundary effects. This

explains the high mobilities, despite the less favourable compact grain morphology.

### 3:40 PM

**W7, In Situ Monitor on the Re-Orientation of Molecular Chains in Operating Organic Devices:** *Tzung-Fang Guo*<sup>1</sup>; Yang Yang<sup>1</sup>; <sup>1</sup>University of California—Los Angeles, Dept. of Matls. Sci. & Eng., 6531 Boelter Hall, Los Angeles, CA 90095 USA

Conjugated polymers are long-chain macromolecules with amorphous structure. When a polymer diode is biased, the polymer chains are subjected to a high electric field in the order of  $10^6$  V/cm. It has long been suspected that polymer chains might undergo some kinds of rearrangement under such strong field. In this presentation, we will report the first successful observation of such rearrangement of polymer chains using the reflection-absorption Fourier transform infrared spectroscopy (RA-FTIR). This method enables the in-situ study of the co-relation between device performance and the conformational transformation of molecular chains. The experimental results indicate that the average direction for the plane of conjugated pi electron cloud in the bulk film was influenced by the external electrical bias. This rearrangement of chains enhances the pi-pi electron coupling and lowers the device operating voltage under a strong electric field.

### 4:00 PM Student

**W8, Electron Diffraction and High Resolution Electron Microscopy of Orthorhombic Crystals in Thermally Evaporated Pentacene Thin Films:** *Lawrence Drummy*<sup>1</sup>; Paul Miska<sup>1</sup>; David Martin<sup>1</sup>; <sup>1</sup>University of Michigan, Matls. Sci. & Eng., 2125 H. H. Dow Bldg., Ann Arbor, MI 48109-2136 USA

Pentacene is a material of current interest for use in organic electronic devices. We have used high-resolution electron optical techniques to investigate the structure and defects in pentacene films. We have characterized a double-herringboned crystal structure found in thin films of pentacene grown by vacuum evaporation onto room temperature mica substrates. Low dose electron diffraction and high-resolution electron microscopy of these crystals together with molecular modeling techniques have allowed us to propose an orthorhombic unit cell with lattice parameters  $a=0.60\text{nm}$ ,  $b=0.73\text{nm}$  and  $c=3.0\text{nm}$ . Figure 1 shows and electron diffraction pattern from the [100] zone of the crystal showing a 3.0nm periodicity along c. The molecules pack in a herringboned arrangement in the a-b plane, as in the well known triclinic pentacene structure, and they also herringbone in the b-c plane, with a nominal molecular tilt of  $20^\circ$  from c.

### 4:20 PM

**W9, Ceramic Superconductor/Organic Polymeric Conductor Nano-Structures:** *Steen B. Schougaard*<sup>1</sup>; John T. McDevitt<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Chem. & Biochem., 24th St. & Speedway, Austin, TX 78712 USA

We present here our initial work towards making a Josephson junction based on a composite of high-temperature copper oxide superconductor and organic conductive polymers. Here the doping of the polymeric conductor serves to influence the distance over which superconductivity may penetrate into the polymer system. The advantages of using a polymer instead of a normal metal or semiconductor is that A) it is easily derivatized to include new functionalities B) it has electrical transport properties that can be changed *reversibly* from a good conductor to an insulator C) it is chemically compatible with the superconductor and does not require high temperature processing that could poison the superconductor. One of the major stumbling blocks when employing soft-solution based chemistry is the inherent instability of the highly oxidized copper oxide superconductor towards common environmental agents like water and  $\text{CO}_2$ . This leads to surfaces on the superconductor that are covered with insulating layer, which effectively inhibits intimate electric connection between polymer and superconductor. However, we present electrochemical data, which shows that employing a SAM (Self Assembled Monolayer) procedure removes the corrosion layer and leaves the SAM in good electrical contact with the surface. The limited range over which this effect is observable ( $<100\text{nm}$ ) sets severe limitations on the techniques that can be used to make the gap between the two superconductor electrodes. We present preliminary data showing patterning of a thin film into a 5000nm wide 300nm thick superconductor bridge by conventional photolithography. This bridge is subsequently severed by a AFM (Atomic Force Microscope) nano-indentation technique leading to

a sub im gab that is easily derivatized with the pyrrole monomer containing the SAM functionality. This in turn ensures good electrical contact to the superconductor and multiple nucleation sites for the following polymerization and doping.

### 4:40 PM

**W10, Optical Switching Responses of Polymer-Based Phototransistors:** *K. S. Narayan*<sup>1</sup>; T. H.B. Singh<sup>1</sup>; Soumya Dutta<sup>1</sup>; <sup>1</sup>Jawaharlal Nehru Centre for Advanced Scientific Research, Chem. & Physics of Matls. Unit, Jakkur PO, Bangalore 560064 India

The prospect of field effect transistor, FET, consisting of organic semiconductor has opened up possibilities of interesting devices. It was recently demonstrated that these polymer-based transistor properties can be controlled optically. This was achieved using a top contact geometry FET with polyvinyl alcohol as the gate insulator and regioregular polyalkylthiophenes as the semiconductor. Some of the interesting features observed, include results which indicate (i) the photo-responsivity at low-light levels ( $<100$  mlux) in the transistor devices is in the order of  $1\text{ A/W}$  (ii) the ON state of the transistor can be accessed either by turning on the gate voltage or with an incident light flux exceeding intensity of  $\sim 20$  microW/cm<sup>2</sup>. The transient-decay response as observed by measuring the  $I_{ds}(t)$  upon switching off the light source is significantly different from the current decay in a surface configured metal-P<sub>3</sub>AT-metal device. The  $I_{ds}(t)$  response in the FET geometry is long-lived with decay time constants in the range exceeding 100 ms. It is also noted that the  $I_{ds}$  decay depended on the gate voltage, with a faster decrease in the depletion mode compared to the floating gate and the enhancement mode. We provide a model for this set of results in terms of the interfacial trap states and diffusion processes in the bulk. We also discuss other strategies to improve the optically-induced responses. The increase in the photosensitivity of the semiconducting polymer can be increased without a significant reduction in the mobility by blending the polymer with electron acceptors. The photo-induced charge transfer process from the polymer to the electron accepting molecule considerably improves the responses. We also present our recent results on photoactive schottky FET where the (gate electrode) aluminum-polymer interface forms a schottky region. We evaluate and compare the light detection performance of these novel photodetectors.

## Session X: Gate Dielectrics - II

Thursday PM      Room: UCEN State Street  
June 27, 2002      Location: University of California

*Session Chairs:* Susanne Stemmer, Rice University, Dept. Mech. Eng. & Matls. Sci., MS 321, 6100 Main St., Houston, TX 77005-3546 USA; T. P. Ma, Yale University, 15 Prospect St., New Haven, CT 06520-8284 USA

### 1:20 PM Invited

**X1, Electronic Structure of Conduction Band States in Transition Metal Oxide, Silicate and Aluminate Alternative High-K Gate Dielectrics:** *G. Lucovsky*<sup>1</sup>; Y. Zhang<sup>1</sup>; G. B. Rayner, Jr.<sup>1</sup>; R. S. Johnson<sup>1</sup>; J. G. Hong<sup>1</sup>; D. Kang<sup>1</sup>; G. Appel<sup>1</sup>; J. L. Whitten<sup>2</sup>; <sup>1</sup>North Carolina State University, Dept. of Physics, Raleigh, NC 27695 USA; <sup>2</sup>North Carolina State University, Dept. of Chem., Raleigh, NC 27695 USA

One of the important issues in high-k alternative gate dielectrics is the tradeoff between increases in k relative to  $\text{SiO}_2$  that permit the use of physically thicker films than  $\text{SiO}_2$  for the same effective capacitance, and reductions in the effective barrier to carrier injection and/or tunneling at the Si/high-k gate dielectric interface. This paper presents a study of the lowest conduction band/anti-bonding states by X-ray absorption spectroscopy (XAS). This study differs from previous studies which have focused on transition metal-atom (TM) and O-atom K edge spectra as for example in Ref. 1, and instead combines O-atom K edge spectra with absorption from n-1 p-states to n d\*-states in the soft X-ray energy regime between 200 and 500 eV (n = 3, 4 and 5). This approach provides greater energy resolution than the TM K edge spectra. Figs. 1, 2 and 3 compare the L<sub>2,3</sub>, M<sub>2,3</sub> and N<sub>2,3</sub> spectra of Sc, Zr and Hf, respectively.

These spectra reveal the two d-state bands that comprise the lowest lying anti-bonding states. The systematic increase in the full-width-at-half-maximum (FWHM) of these spectral features with increasing  $n$  is a manifestation of the spatial localization of the initial  $n-1$  p-states and final  $n$  d\*-states on the respective TM atoms. The FWHM scales as the cube of effective atomic number,  $Z_{\text{eff}}$ , indicating that the FWHM reflects a lifetime broadening due to the relatively high  $Z$  values. The dependence on  $Z_{\text{eff}}$  is essentially the same as that of the spin-orbit splitting of the  $n-1$  p-states. The K edge spectra provide complementary information, and comparisons between spectra of transition metal oxides, e.g.,  $\text{HfO}_2$ , and Hf silicate and aluminate alloys identifies differences in the overlap between the anti-bonding TM d\*-states, and TM, silicon and/or aluminum s\*-states. Differences between the energies of the d\*-states and s\*-states in  $\text{ZrO}_2$  between the Zr M2,3 and O K1 spectra indicate relatively strong final-state or excitonic effects. Ab-initio calculations on relatively small clusters confirm the excitonic nature of the final state effects; e.g., they explain the almost 4 eV difference between the d\*- and s\*-anti-bonding states in the Zr M2,3 and O K1 spectra. In addition, they provide additional insight into the differences in effective band gap and/or barrier height derived from photoconductivity and internal photoemission studies on  $\text{ZrO}_2$  [2] and  $\text{HfO}_2$  [3]. Extension of these studies to group IIIB oxides,  $\text{Y}_2\text{O}_3$  and  $\text{La}_2\text{O}_3$  confirms that relative differences in energy between the d\*- and s\*-anti-bonding states scale with calculated atomic states in the  $n-1$ dm-ns2 configurations that are the appropriate basis states for oxide properties. Finally, the paper addresses the relationship between the effective barrier to carrier injection and/or tunneling at the Si-high-k gate dielectric interface, and i) the TM and rare earth (RE) lanthanide atomic  $n$  d- and  $n+1$  s-states, and ii) the anti-bonding  $n$  d\*- and  $n+1$  s\*-states determined from the different types of spectroscopic studies identified above.

#### 2:00 PM

**X2, EXAFS Measurements of Crystallization of  $\text{ZrO}_2$  Dielectric Films:** Charles Bouldin<sup>1</sup>; Debra Kaiser<sup>1</sup>; Joe Ritter<sup>1</sup>; <sup>1</sup>NIST, Ceram., 100 Bureau Dr., Stop 8522, Gaithersburg, MD 20899 USA

Two of the key materials issues in the development of alternate gate dielectric layers with electrical performance comparable to silicon dioxide are crystallinity and homogeneity. In this work, we use extended x-ray absorption fine structure (EXAFS), high resolution transmission electron microscopy (HRTEM), energy dispersive x-ray spectrometry (EDS) and glancing angle x-ray diffraction (XRD) to study crystallization behavior and homogeneity in ultra-thin (<5 nm) metal-oxide films. We deposit Zirconium oxide films by spin-coating solutions containing several metal precursors, (such as zirconium acetate), propylene glycol, isopropanol and glacial acetic acid onto (100) Si wafers, which are then dried and annealed. Solution compositions and spin conditions are selected to give films with a thickness of about 5-10nm as determined by HRTEM. The films are then annealed at 800-900C to simulate the time-at-temperature annealing required for fabricating typical device structures. We find that spin-coating can produce films of uniform thickness and composition with very smooth interfaces, even in the extremely thin 5nm thickness range. EXAFS shows that the films as-deposited and after drying (at about 200C) are amorphous, but that higher temperature annealing, above about 550C, results in poly-crystalline films. The crystallization is monitored using EXAFS and observing the relaxation in the Zr-O-Zr bond angle. This technique for determining crystallization is non-destructive and samples the entire film area. In selected samples, the observation of crystallization is confirmed by HRTEM.

#### 2:20 PM

**X3, Structure and Stability of Gd- and La-Based High-K Films on Si(100):** Xiaohua Wu<sup>1</sup>; Dolf Landheer<sup>1</sup>; Terry Quance<sup>1</sup>; Mike J. Graham<sup>1</sup>; Gianluigi A. Botton<sup>2</sup>; <sup>1</sup>National Research Council of Canada, Inst. for Microstruct. Scis., M-50, 1200 Montreal Rd., Ottawa, Ontario K1A 0R6 Canada; <sup>2</sup>McMaster University, Matls. Sci. & Eng., 1280 Main St. W., Hamilton, Ontario L8S 4L7 Canada

The structure and stability of gadolinium and lanthanum oxide and silicate films deposited on Si(100) substrates using electron-beam evaporation from pressed-powder targets have been studied by high-resolution transmission electron microscopy (HRTEM), electron energy loss spectroscopy (EELS) and selected area electron diffraction (SAED). As-deposited oxide films consist of a crystalline oxide layer and an amorphous interfacial layer, while as-deposited silicate films consist of an amorphous silicate layer without an interfacial layer. After annealing in

oxygen, an interfacial  $\text{SiO}_2$ -rich silicate layer is formed in both oxide and silicate films. The formation of interfacial silicate layers is found to be thermodynamically more favorable for the La-based films than for the Gd-based films. The gadolinium silicate,  $(\text{Gd}_2\text{O}_3)_{0.45}(\text{SiO}_2)_{0.55}$  film crystallizes at a temperature between 1000°C and 1050°C, while the crystallization temperature for the lanthanum silicate,  $(\text{La}_2\text{O}_3)_{0.45}(\text{SiO}_2)_{0.55}$  film is between 900°C and 950°C.

#### 2:40 PM Student

**X4, An Electron Spin Resonance Observation of Hafnium Oxide Thin Films for Advanced Gate Dielectrics:** Andrew Y. Kang<sup>1</sup>; Patrick M. Lenahan<sup>1</sup>; John F. Conley, Jr.<sup>2</sup>; <sup>1</sup>Pennsylvania State University, Eng. Sci. & Mech., 212 Earth & Eng. Sci. Bldg., University Park, PA 16802 USA; <sup>2</sup>Sharp Labs of America, Matls. Rsrch., 5700 NW Pacific Rim Blvd., Camas, WA 98607 USA

We have initiated a study of one of the most promising high k dielectric materials, atomic layer chemical vapor deposited (ALCVD) hafnium oxide ( $\text{HfO}_2$ ) on silicon, using electron spin resonance (ESR) and electrical measurements. We adapted a tactic utilized in very early ESR investigations of MOS systems, taking advantage of the simplicity of the (111) Si/dielectric interface. (Later ESR studies on the more important but more complex (100)Si interface demonstrated the (111) studies were relevant to the problems at hand). The as-deposited films were ~15nm thick. Measurements were made on samples as deposited and subjected to a 60 sec, 400°C anneal in forming gas. X-ray diffraction shows that these thin  $\text{HfO}_2$  films are amorphous as deposited and remain amorphous after the 400°C anneal. A thin layer of lower-k material, possibly a silicate is observed. Fig. 1 shows ESR spectra of an ALCVD  $\text{HfO}_2$  film on (111) Si (a) as deposited and (b) after a 60 sec, 400°C forming gas anneal. We observe several types of dangling bond (db) defects at the  $\text{HfO}_2$ /(111)Si boundary. The strongest signal in Fig. 1 is designated  $\text{HfO}_2$ ldb (hafnium oxide interface dangling bond). The g tensor of the  $\text{HfO}_2$ ldb defect has an axis of symmetry corresponding to the (111) surface normal with  $g(\text{parallel}) = 2.0018$  and  $g(\text{perpendicular}) = 2.0094$ . The g tensor values are somewhat similar but not the same as those of the (111) Si/ $\text{SiO}_2$   $P_b$  and the (100) Si/ $\text{SiO}_2$   $P_{b0}$  interface db, in both cases  $g(\text{parallel}) = 2.0013$  and  $g(\text{perpendicular}) = 2.0081$ . Moderate differences in the g tensor indicate that the  $\text{HfO}_2$ ldb defect is a Si/ $\text{HfO}_2$  interface silicon db, but with higher p character electron wave function than the conventional (111)  $P_b$  center. Weaker signals indicate the presence of back-bonded Si dbs pointing into the Si substrate, suggesting the presence of terracing in these samples. Forming gas anneal results indicate db defects in  $\text{HfO}_2$ /Si system responds about the same as  $\text{SiO}_2$ /Si dbs to hydrogen passivation. The forming gas anneal greatly reduces the number of dbs at the interface. Representative CV measurements shown in Fig. 2 also indicate a corresponding decrease in the interface state density. Some samples were also exposed vacuum ultraviolet (VUV) illumination. Results indicate the stability of (presumably) SiH sites at the  $\text{HfO}_2$ /Si boundary is very different than those at the Si/ $\text{SiO}_2$  boundary. SiH in the  $\text{HfO}_2$ /Si samples sites are not very susceptible to bond breaking events to which SiH sites in the Si/ $\text{SiO}_2$  system are extremely sensitive.

#### 3:00 PM Break

#### 3:20 PM

**X5, Physical and Electrical Characteristics of  $\text{ZrO}_2$  Thin Films as a Promising Gate Dielectrics:** Jung-Ho Yoo<sup>1</sup>; Seok-Woo Nam<sup>1</sup>; Suheun Nam<sup>1</sup>; Dae-Hong Ko<sup>1</sup>; Ja-Hum Ku<sup>2</sup>; Cheol-Woong Yang<sup>2</sup>; <sup>1</sup>Yonsei University, Ceram. Eng., 134 Shinchon-dong, Seodaemun-gu, Seoul 120-749 S. Korea; <sup>2</sup>Samsung Electronics Company, Ltd., R&D, San #24 Nongseo-Ri, Kiheung-Eup, Yongin, Kyungki-Do 449-900 S. Korea; <sup>3</sup>Sungkyunkwan University, Matl. Sci., 300 Chunchun-Dong, Changan-Gu, Suwon, Kyungki-Do 440-746 S. Korea

As complementary metal oxide semiconductor (CMOS) devices are being continuously scaled, oxide layers with an equivalent oxide thickness thinner than 15Å will be required. However, the ultrathin  $\text{SiO}_2$  layers shows a direct tunneling of carriers through the potential barrier, leading to significant leakage current at operating voltage. Therefore, dielectric materials with higher dielectric constant than  $\text{SiO}_2$ , possibly large band-gap, low interface state density, and good thermal stability have drawn a lot of attention as alternative gate dielectric materials. Recently,  $\text{ZrO}_2$ ,  $\text{HfO}_2$ ,  $\text{La}_2\text{O}_3$  and their silicates have been considered as promising alternative materials due to their high dielectric constant and good thermal stability with Si substrates. We investigated the changes of



the microstructures and electrical properties of both the ZrO<sub>2</sub> film and the interface between the film and Si (100) substrate with deposition and annealing conditions. And the electrical properties and thermal stability on sputtered ZrO<sub>2</sub> films with various electrodes for p-type silicon substrate were compared. ZrO<sub>2</sub> thin films as a gate dielectric were deposited by reactive dc magnetron sputtering, followed by thermal annealing in N<sub>2</sub> gas ambient using furnace and subsequently the microstructures of ZrO<sub>2</sub> and the interface were investigated by Ellipsometry, XRD, AFM, TEM and XPS. The ZrO<sub>2</sub> films deposited at elevated temperatures are polycrystalline, and both the monoclinic and tetragonal phases exist in the films. The films with higher density and improved crystallinity are obtained at higher deposition temperatures. The interfacial oxide layer between ZrO<sub>2</sub> films and Si substrates grew upon annealing in the N<sub>2</sub> gas ambient, which is due to the oxidation of Si substrates by the diffusion of oxidizing species from N<sub>2</sub> gas ambient. And then various metals such as Al, Pt, TiN and TiN/Al were deposited by sputtering as a gate electrode. Also, conventional poly-Si and poly-SiGe as a gate electrode were deposited by chemical vapor deposition. By HRTEM, XPS/AES and SIMS analyses, we evaluated compatibility and thermal stability between the ZrO<sub>2</sub> films and electrodes. We focused on the interfacial layer between high-k dielectric and electrodes. The electrical properties were assessed by C-V and I-V measurements of Metal-Oxide-Semiconductor capacitor structure. In comparison with Pt electrode, ZrO<sub>2</sub> films with Al electrode demonstrated about 8% degradation due to Al-O amorphous interlayer. At the higher annealing temperature, a reaction of ZrO<sub>2</sub> film with poly-Si was observed. And we compared electrical characteristics upon various electrodes.

### 3:40 PM

**X6, The Characteristics of HfO<sub>2</sub> Thin Films as Gate Dielectrics:** *Seok-Woo Nam<sup>1</sup>; Jung-Ho Yoo<sup>1</sup>; Suheun Nam<sup>1</sup>; Dae-Hong Ko<sup>1</sup>; Ja-Hum Ku<sup>2</sup>; Cheol-Woong Yang<sup>3</sup>; <sup>1</sup>Yonsei University, Ceram. Eng., 134 Shinchon-dong, Sodaemun-gu, Seoul 120-749 S. Korea; <sup>2</sup>Samsung Electronics Company, Ltd., R&D, San #24 Nongseo-Ri, Kiheung-Eup, Yongin, Kyungki-Do 449-900 S. Korea; <sup>3</sup>Sungkyunkwan University, Matl. Sci., 300 Shunchun-Dong, Changan-Gu, Suwon, Kyungki-Do 440-749 S. Korea*

Silicon Dioxide has been used as the primary gate dielectric material in MOSFET devices for over 40 years. As the thickness of SiO<sub>2</sub> decreases, a direct tunneling of carriers through the potential barrier occurs, which results in the significant leakage current through the SiO<sub>2</sub> layer. Because of this issue, a conventional SiO<sub>2</sub> process shows limitation in the fabrication of CMOS devices in sub-1.5nm thickness regime. Therefore, the development of alternative dielectric materials is required for the fabrication of sub-0.1μm MOSFET devices. Dielectric materials with a high dielectric constant, large band-gap, low interface state density, and good thermal stability have drawn a lot of attention as alternative gate dielectric materials. Recently, HfO<sub>2</sub>, ZrO<sub>2</sub> and their silicates have been considered as promising alternative materials due to high dielectric constant and good thermal stability with Si substrates. We evaluated the HfO<sub>2</sub> films deposited by the conventional reactive sputtering. The HfO<sub>2</sub> thin films on (100) silicon substrate treated by a HF solution and were deposited by reactive dc magnetron sputtering for gate dielectric application, followed by Pt sputtering for gate electrode. During hafnium sputtering, O<sub>2</sub> was modulated to control the interface quality and to suppress the additional growth of the interfacial layer. Samples were then post-annealed by using furnace. The resulting films were analyzed by ellipsometry, XRD, HRTEM, RBS, and XPS/AES. According to the annealing and deposition methods, films showed different phase transition. By HRTEM and XPS/AES analyses, we observed the properties of HfO<sub>2</sub> films and the interfacial layers between the HfO<sub>2</sub> films and the Si substrate upon annealing and deposition methods. The films with Hf metal layer showed the reduced interlayer. The electrical properties were assessed by C-V and I-V measurements for MOS structures. As the films suffered heat treatment, leakage current characteristics were improved whereas the accumulation capacitances were degraded due to the growth of the interfacial layer. The flatband voltage shifted negatively which correlated with the positive fixed charges and post annealing in O<sub>2</sub> was seen to decrease the net amount of positive charges.

### 4:00 PM

**X7, Interfacial Reaction Between Poly SiGe and ZrO<sub>2</sub> with Ge Content in the Poly SiGe Films:** *Sung-Kwan Kang<sup>1</sup>; Jung-Ho Yoo<sup>1</sup>; Seok-Woo Nam<sup>1</sup>; Dae-Hong Ko<sup>1</sup>; Han-Byul Kang<sup>2</sup>; Chul-Woong Yang<sup>2</sup>; <sup>1</sup>Yonsei University, Ceram. Eng., 134, Sodaemoon-ku, Seoul 120-749 S. Korea;*

<sup>2</sup>Sung Kyun Kwan University, Adv. Matl. Eng., Chunchun-dong, Suwon 150-150 S. Korea

Recently, high K dielectrics have been suggested as alternatives to the currently employed SiO<sub>2</sub> gate dielectric for complementary metal oxide semiconductor (CMOS) technology due to low leakage current at a same Tox. Several high K dielectric materials have been investigated as an alternative gate dielectric, however, their application is limited due to the interfacial reaction between high k materials and Si substrate during the post process. Among the suggested materials, ZrO<sub>2</sub> films have many advantages, such as a high dielectric constant (15~22), a relatively large band gap (5.2~7.8 eV) and so on. In addition to the above advantages, ZrO<sub>2</sub> films must be thermally stable with gate electrode during the deposition of gate electrode films and post process for the compatibility with the conventional process to apply to gate dielectric. However, in the case of deposition of poly Si on high K dielectrics, silicide was formed between poly Si and high K dielectrics during annealing and resulted in the increase of leakage current of devices. In order to prevent the silicidation and other advantages, such as lower resistivity and controllable work-function, we deposited poly Si<sub>1-x</sub>Ge<sub>x</sub> films onto high K dielectrics as a gate electrode. Previously, it was reported that silicide formation was retarded due to the Ge of poly Si<sub>1-x</sub>Ge<sub>x</sub> in the Co/Si<sub>1-x</sub>Ge<sub>x</sub>, Ti/Si<sub>1-x</sub>Ge<sub>x</sub> system. After standard cleaning of the p-type silicon wafer, 5.8nm thick ZrO<sub>2</sub> films were deposited at room temperature (R.T.) by reactive DC magnetron sputtering from a Zr target with 99.9% purity in Ar+O<sub>2</sub> gas ambient and 10nm thick poly Si films were grown on ZrO<sub>2</sub> films at 600°C using low pressure chemical vapor deposition (LPCVD) system. After deposition, the films were annealed for 30 min at 800°C and 900°C. High resolution transmission electron microscopy (HR-TEM) and X-ray photoelectron spectroscopy (XPS) were used to study the interfacial reaction between poly Si<sub>1-x</sub>Ge<sub>x</sub>(x=0, 0.2, 0.4) and ZrO<sub>2</sub> films. To investigate the chemical state of poly Si<sub>1-x</sub>Ge<sub>x</sub>(x=0, 0.2, 0.4)/ZrO<sub>2</sub>, ZrO<sub>2</sub> films, ZrO<sub>2</sub>/IL, and IL/Si substrate, initially, poly Si films were etched to poly Si<sub>1-x</sub>Ge<sub>x</sub>(x=0, 0.2, 0.4)/ZrO<sub>2</sub> interface by Ar sputtering in XPS chamber and then, core level spectra of Zr 3d, O 1s, and Si 2p were obtained at each etching step from the poly Si<sub>1-x</sub>Ge<sub>x</sub>(x=0, 0.2, 0.4)/ZrO<sub>2</sub> interface to IL/Si substrate. In addition, as-deposited ZrO<sub>2</sub> films were annealed in high vacuum ambient (vacuum < 1E-7 torr) for 10 min to investigate the effect of the gate electrode deposition temperature (600°C) on the ZrO<sub>2</sub> films by using HR-TEM and XPS.

### 4:20 PM Student

**X8, Electrical and Materials Characteristics of Pr<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>:** *Sanghun Jeon<sup>1</sup>; Hyunsang Hwang<sup>1</sup>; <sup>1</sup>Kwangju Institute of Science and Technology, Dept. of Matls. Sci. & Eng., Gwangju 500-712 S. Korea*

As MOS devices scaled down, thermally stable high K gate dielectrics are required. Thus several groups have investigated on thermally stable high K materials such as HfO<sub>2</sub>, and ZrO<sub>2</sub>, and its silicate by means various processes. However, various electrical properties of lanthanide-silicate gate dielectric have not been reported yet. We investigated electrical and material properties of Pr<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> (Pr-silicate) by rapid thermal oxidation of Pr thin metal layer on Si. The formation of the mixture of Pr<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> as the results of rapid thermal oxidation of Pr layer on Si can be explained by high reactivity of Pr with Si and O<sub>2</sub> and the large difference of ionic radius between Pr atoms and Si atoms. After high temperature anneal process, Si atoms from Si substrate can be easily incorporated into Pr layer. As a result, PrSi<sub>x</sub>O<sub>y</sub> was prepared. By observation of the O1s loss spectrum shown in Fig 1, the coexistence of hydroxide, silicon oxide and praseodymium oxide was observed. Based on the XPS result, the portion of Pr<sub>2</sub>O<sub>3</sub> in PrSi<sub>x</sub>O<sub>y</sub> was about 19%. Equivalent oxide thickness (EOT) of an ultrathin Pr<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> oxide by rapid thermal oxidation within negligible dispersion was scaled down to 1.3nm with a leakage current density less than 3×10<sup>-3</sup> A/cm<sup>2</sup> at Vfb-1V. The effect of various process conditions such as interfacial nitridation, and oxidation temperature and pressure on electrical characteristics of PrSi<sub>x</sub>O<sub>y</sub> was studied. It was found that interfacial nitridation causes the degradation of electrical properties such as the increase of fixed oxide charge, and large hysteresis characteristics shown in Fig 2 A. However, with increasing process temperature, the electrical properties of Pr<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> was enhanced without the degradation of electrical oxide thickness. The compatibility of poly-Si with this high K material was confirmed. From C-J characteristics, it was found that the leakage current density of Pr<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> was a two orders magnitude reduction compared to a leakage current of SiO<sub>2</sub>. We have investigated conduction mechanism of poly-Si/Pr-silicate/Si. Poole-Frenkel conduction



mechanism can explain IV characteristics of Pr silicate. We also investigated MOSFET characteristics with 1.8nm(effective oxide thickness)-thick Pr silicate. Considering high subthreshold swing of 97mV/dec shown in Fig 2 B, the improvement of interface state density is necessary for MOSFET application.

#### 4:40 PM

**X9, Atomic Layer Deposition of ZrO<sub>2</sub> Thin Films:** Anil Mane<sup>1</sup>; Arpan Chakraborty<sup>2</sup>; M. P. Singh<sup>1</sup>; M. S. Dharmaprasanth<sup>1</sup>; V. Venkataraman<sup>2</sup>; S. A. Shivashankar<sup>1</sup>; <sup>1</sup>Indian Institute of Science, Matls. Rsrch. Ctr., Bangalore, Karnataka 560012 India; <sup>2</sup>Indian Institute of Science, Dept. of Physics, Bangalore, Karnataka 560012 India

During the last two decades, silicon dioxide has been used as the gate dielectric material for standard CMOS technology. One of the problems with scaling MOSFETs beyond the 0.1 μm technology is the increase in the leakage current through the gate dielectric. The technology roadmap for semiconductors indicates that the present rate of device scaling will produce devices with a feature size of 100nm with an equivalent gate oxide thickness of 1.5-2nm. ZrO<sub>2</sub> is a candidate to replace SiO<sub>2</sub> as it has a high dielectric constant, large band gap, is thermodynamically stable, and can be deposited with predictable thickness by atomic layer deposition (ALD) at low temperature. Atomic layer deposition (ALD) is a chemical process for the layer-by-layer formation of thin films, based on the self-limiting adsorption of the precursor vapours on the heated substrate surface. The vapours are pulsed into the reactor, the pulses separated by a purging or evacuation period. Each precursor pulse saturates the substrate surface with a mono-molecular layer of the precursor. This results in a unique self-limiting film growth process with several advantages, such as excellent conformity, uniformity over large area, and digital film thickness control. Therefore, it is possible to grow via ALD high quality ultra-thin films of metal oxides, compound semiconductors, as well as multilayers. In an ALD reactor built in house, we have deposited thin films of zirconium oxide on Si(100) substrate using the Zirconium (IV) acetylacetonate under various deposition conditions, such as different ALD cycles, pressures, temperatures (350-550°C), and gas flow rates. X-ray diffraction (XRD) analysis of these films shows that, depending on the deposition conditions, the films are amorphous and polycrystalline in nature, as confirmed by transmission electron microscopy (TEM). At higher temperatures, crystallites of various sizes are present in the films. The surface morphology and microstructure of these films have been studied by scanning electron microscopy (SEM), showing that the deposited films are uniform over ~1.5 cm<sup>2</sup>. FTIR analysis shows the presence of carbon in the films, which is confirmed by x-ray photoelectron spectroscopy (XPS). Dielectric measurements have been carried out on amorphous and polycrystalline films with thicknesses ranging from 30-100nm, to assess whether would qualify as gate dielectric layers. C-V measurements show hysteresis widths as small as ~100-200 mV, with the dielectric constant values in the range ~19-24. The interface state density and the leakage current density are found to be small. Interface electron mobility of 450 cm<sup>2</sup>/V-s was measured. The details of the ALD process for ZrO<sub>2</sub> thin films, the growth kinetics, and the microstructure and electrical properties of the films will be presented in the conference.

## Session Y: Epitaxy: Arsenide Nitrides

Thursday PM      Room: UCEN Lobero  
June 27, 2002      Location: University of California

*Session Chair:* Rachel S. Goldman, University of Michigan, Dept. of Matls. Sci. & Eng., Ann Arbor, MI 48109-2136 USA

#### 1:20 PM Student

**Y1, Effects of Arsenic Flux on the Stress Evolution and Optical Properties of GaAsN Films Grown by Reactive Molecular Beam Epitaxy:** Matthew Reason<sup>1</sup>; Weifeng Ye<sup>1</sup>; Xiaojun Weng<sup>1</sup>; Rachel S. Goldman<sup>1</sup>; <sup>1</sup>University of Michigan, Matl. Sci. & Eng., 2300 Hayward, H. H. Dow Bldg., Ann Arbor, MI 48109-2136 USA

Narrow gap nitride alloys have shown significant promise for a wide range of applications including long-wavelength light emitters and de-

tectors, high performance electronic devices, and high efficiency solar cells. In the narrow gap nitride alloy system, the evolution of film strain relaxation and its effects on the optical properties of the films are not well understood. In this work, we have examined the effects of arsenic flux on the stress evolution and optical properties of GaAsN films grown by solid-source molecular beam epitaxy (MBE) using an N<sub>2</sub>-RF plasma source. The samples consisted of 500nm buffer layers of GaAs grown at 580C and 20nm layers of GaAs grown at 500C, both using a high arsenic flux; followed by 100nm layers of GaAsN grown at 400C using a 10% N<sub>2</sub>/Ar gas mixture at a 0.15 sccm flow rate, with a variety of arsenic beam equivalent pressures (BEP's). The structure and properties of the samples were investigated by reflection high energy electron diffraction (RHEED), multi-beam optical stress sensor (MOSS), high resolution x-ray diffraction, nuclear reaction analysis, atomic force microscopy, and photoluminescence. As the arsenic BEP is increased from 4 x 10<sup>-6</sup> to 1.1 x 10<sup>-5</sup> Torr, the nitrogen concentration in GaAsN increases from 0.6 to 0.9%, suggesting that N-As exchange plays a significant role in the incorporation of N into the film. For all of the arsenic fluxes studied, in-situ RHEED during the GaAsN layer growth reveals a pattern similar to that observed during the growth of the GaAs layers. Interestingly, for the highest arsenic flux studied, in-situ MOSS reveals a transition in the mode of strain relaxation after ~50nm of film growth. We will discuss the effects of arsenic flux on the stress relaxation and optical properties of a variety of GaAsN and InGaAsN films and heterostructures. This work was supported in part by the DOE (Photovoltaics Beyond the Horizon Program), the Air Force Office of Scientific Research (MURI Program), and the TRW Foundation.

#### 1:40 PM Student

**Y2, Strain-Induced Valence Band Splitting in Bulk GaNAs Grown by Gas Source MBE:** Y. G. Hong<sup>1</sup>; A. Y. Egorov<sup>1</sup>; C. W. Tu<sup>1</sup>; <sup>1</sup>University of California-San Diego, Dept. of Electl. & Compu. Eng., La Jolla, CA 92093-0407 USA

Recently, Ga(In)NAs alloy system has attracted a great deal of attention due to its potential applications in multijunction solar cells, 1.3 μm vertical cavity surface emitting lasers, and heterojunction bipolar transistor. The incorporation of a very small amount of nitrogen (less than a few percent) into GaAs and related materials leads to a dramatic decrease in the bandgap energy, which has been explained by the interaction of a narrow band of quasilocalized N-states with the extended conduction band states. Meanwhile the smaller nitrogen atom reduces the lattice parameter of GaN<sub>x</sub>As<sub>1-x</sub>, which introduce the strain in the epilayer. In growth on GaAs substrates, however, this problem is significantly alleviated by the pseudomorphic strain which counteracts the unfavorable enthalpy of mixing. Coherency with the substrate greatly suppresses the tendency for phase separation into the components, GaAs and GaN. The pseudomorphic growth of strained GaN<sub>x</sub>As<sub>1-x</sub> layers on GaAs substrates leads to the changing of conduction and valence band energies and to an additional splitting of the valence-band energies. In this paper we present this behavior in GaN<sub>x</sub>As<sub>1-x</sub> layers grown on GaAs. Strained GaN<sub>x</sub>As<sub>1-x</sub> layers, 0.1 μm thick, were grown by gas-source molecular beam epitaxy on (001) GaAs semi-insulated substrates. The nitrogen alloy content was varied in the range 2-3.4%. The quality, strain and alloy content of grown GaN<sub>x</sub>As<sub>1-x</sub> layers were examined by high-resolution X-ray diffraction. The twin peaks photoluminescence of GaN<sub>x</sub>As<sub>1-x</sub> grown on GaAs was observed at room temperature. The peak splitting increases with increase in nitrogen composition. This peak splitting at room temperature becomes pronounced for GaN<sub>x</sub>As<sub>1-x</sub> layers with nitrogen alloy concentration more than 1.5%. For lower concentration the homogeneous and inhomogeneous broadening of PL line screens this splitting. The effect of strain on energy levels can be decomposed into hydrostatic and shear contributions. Both contributions affect the conduction band for zincblende-type semiconductors at G point. The hydrostatic strain component leads to a shift of average valence-band energy, i.e., the average of the energies of the heavy-hole, light-hole, and spin-orbit split-off bands. The shear contribution couples to the spin-orbit interaction and leads to an additional splitting of the valence-band energies. The comparison of the results of calculation with the experimental data of energy splitting let us conclude that we experimentally observed light- and heavy-hole transition in GaN<sub>x</sub>As<sub>1-x</sub>.

## 2:00 PM Student

**Y3, Deep Levels in GaAs<sub>1-x</sub>N<sub>x</sub> Grown on GaAs by Molecular Beam Epitaxy:** *Ri-an Zhao*<sup>1</sup>; Michael J. Cich<sup>1</sup>; Henning Feick<sup>1</sup>; Petra Specht<sup>1</sup>; Eicke R. Weber<sup>1</sup>; <sup>1</sup>University of California–Berkeley, Matls. Sci. & Eng., 211-226, Berkeley, CA 94720 USA

We have studied deep levels in GaAs<sub>1-x</sub>N<sub>x</sub> (x ~ 0.8%) epilayers using deep-level transient spectroscopy (DLTS). The samples were grown pseudomorphically on GaAs substrates by molecular beam epitaxy (MBE) using a DC plasma source for the activated nitrogen species. For as-grown n-GaAsN, five electron traps were detected: E1(0.31eV), E2(0.28eV), E3(0.39eV), E4(0.47eV) and E5(0.60eV), with the activation energies given relative to the conduction band edge. The electron capture cross section for the dominant trap E3 was measured using the variable pulse width method. Annealing experiments showed that the deep traps are stable up to 600°C. Higher temperature annealing is investigated as a means to reduce the deep level concentration. The DLTS results will be directly correlated with photoluminescence (PL) measurements and other optical characterization techniques. The microscopic origin of the deep level traps will be discussed in the framework of the impurities introduced during the MBE growth as well as the ion damage induced by the nitrogen plasma source.

## 2:20 PM

**Y4, Long Wavelength, High Efficiency Photoluminescence from MBE Grown GaInNAsSb:** *Vincent Gambin*<sup>1</sup>; Wonil Ha<sup>1</sup>; Mark Wistey<sup>1</sup>; James Harris<sup>1</sup>; Seongsin Kim<sup>2</sup>; <sup>1</sup>Stanford University, Electl. Eng., CIS-X, Stanford, CA 94305 USA; <sup>2</sup>Agilent Technologies, Electl. Eng., 395 Page Mill Rd., Palo Alto, CA 94303 USA

Dilute nitride GaInNAs has recently been found to optically emit at wavelengths longer than previously possible for material epitaxially grown on GaAs substrates. This material system is promising as an active region for use in 1.3 and 1.55 μm optoelectronic devices. Adding small amounts of nitrogen to GaAs alloys preserves direct gap properties and can decrease the bandgap while shrinking the lattice constant. Adding nitrogen to GaInAs pushes emission to longer wavelengths and offsets the indium lattice mismatch making higher indium concentrations possible with strained epitaxy. However an upper limit to nitrogen incorporation exists due to a large miscibility gap between the GaAs and GaN systems. GaNAs tends to phase segregate at high nitrogen concentrations resulting in an inhomogeneous material. Nitride-arsenide alloys were grown by elemental source MBE using a radio frequency (RF) nitrogen plasma cell. Substrate growth temperatures were kept low, kinetically limiting phase segregation, thereby incorporating much more nitrogen than is thermodynamically stable. High nitrogen content materials grown at low temperatures do not initially exhibit strong optical emission. The defects generated during the growth are a source for non-radiative recombination and diminish photoluminescence (PL). By rapid thermal annealing the material after growth, defects are removed from the active region and the crystal quality of the GaInNAs films significantly improves. However during anneal nitrogen diffuses out from the quantum well and blue-shifts optical emission. Specific changes that occur on anneal have been studied using techniques such as Secondary Ion Mass Spectrometry (SIMS), Nuclear Reaction Analysis Rutherford Backscattering Spectrometry (NRA-RBS), and Cathode Luminescence (CL). Two techniques were investigated to expand the feasible emission wavelengths for this material system. GaNAs barriers between GaInNAs quantum wells reduce the blue shift due to nitrogen out-diffusion and can be designed to strain compensate highly compressive GaInNAs. Sb present during GaInNAs growth has been thought to act as a surfactant and improve photoluminescence. With the addition of Sb, we have observed a sharp intensity increase with high In samples past 1.3 μm and found it not only acts as a surfactant but it is a significant alloy constituent further red-shifting the optical emission. Increasing In and N in materials with PL over 1.3 μm normally drops optical intensity, however using Sb we can maintain high PL intensity out to 1.6 μm. Since Sb in GaAs is compressively strained, there is further need for GaNAs strain compensating barriers for applications in multiple quantum well, high-intensity devices. Towards this goal, we have grown GaInNAsSb multiple quantum well devices on GaAs that exhibit high-intensity optical emission across the 1.3-1.6 μm wavelength range.

## 2:40 PM

**Y5, The Photoluminescence of Epitaxial InGaAs for 1.3 Micron GaAs-Based Optoelectronic Devices:** *Jessica MacLean*<sup>1</sup>; Keith Nash<sup>1</sup>;

Philip Calcott<sup>2</sup>; <sup>1</sup>QinetiQ, Ltd., Optoelectronic Components, M345, Malvern Tech. Ctr., Malvern, Worcs. WR14 3PS UK; <sup>2</sup>QinetiQ, Ltd., Microwave Sensors, M345, Malvern Tech. Ctr., Malvern, Worcs. WR14 3PS UK

GaAs-based 1.3 and 1.55 micron dilute nitride devices, such as edge-emitting lasers, vertical cavity surface emitting lasers (VCSEL's) and photodetectors, have the potential to enhance performance and reduce the cost of a number of types of optical communications modules. The GaAs-based 1.3 micron VCSEL has the advantage of the use of standard alloys (GaAs, AlAs) for the high reflectivity mirrors and such devices, grown by Molecular Beam Epitaxy (MBE) using a plasma source of nitrogen, are being transferred to production, the first dilute nitride devices to do so. The use of an alkyl precursor as the nitrogen source allows relatively simple scale-up for production, as compared with a plasma source. However, the Metalorganic Vapour Phase Epitaxy (MOVPE) growth using 1,1-Dimethylhydrazine (DMHy) of indium gallium nitride arsenide (InGaNAs) emitting at 1.3 micron and beyond is challenging due to the high flows nitrogen precursor required and the low nitrogen incorporation efficiency. This study reports the epitaxy and photoluminescence of InGaNAs quantum wells by Chemical Beam Epitaxy (CBE) using trimethylindium (TMIn), triethylgallium (TEGa), arsine and DMHy as the nitrogen precursor. The work builds on a previous study which demonstrated very high nitrogen incorporation into GaAs by CBE (up to 7% retaining single phase GaNAs). The growth temperature, V:III ratios and compositions have been varied using indium percentages in the range (15-35)% and measuring the substitutional nitrogen incorporation by temperature-variable photoluminescence. Optimisation of the growth parameters has resulted in an intensity enhancement of the low temperature PL (10 K) beyond 1 micron by several orders of magnitude. The requirement for high photoluminescence efficiency is a prerequisite for the fabrication of a 1.3 micron laser device using this novel quaternary material.

## 3:00 PM Break

## Session Z: Epitaxy: Devices

Thursday PM      Room: UCEN Lobero  
June 27, 2002      Location: University of California

*Session Chair:* Pat Grillot, LumiLeds Lighting, US LLC, R&D, 370 W. Trimble Rd., San Jose, CA 95131 USA

## 3:20 PM Student

**Z1, Molecular Beam Epitaxial Growth of InAs Bipolar Transistors:** *Kent L. Averett*<sup>1</sup>; Shimon Maimon<sup>2</sup>; Xiaohua Wu<sup>1</sup>; Mike W. Koch<sup>2</sup>; Ahmed Elnaggar<sup>2</sup>; Gary W. Wicks<sup>2</sup>; <sup>1</sup>University of Rochester, Dept. of Physics & Astron., Wilmot Bldg., Rochester, NY 14627 USA; <sup>2</sup>University of Rochester, Inst. of Optics, Wilmot Bldg., Rochester, NY 14627 USA

InAs shows promise as a material for electronic devices due to its large electron mobility and large saturation velocity. The historical trend to increase the InAs content in GaInAs bipolar and field effect transistors has led to increased performance. The ultimate conclusion of this trend is the construction of transistors of pure InAs. The present work involves materials and device investigations related to InAs-based bipolar transistors grown by molecular beam epitaxy (MBE). Initial materials studies produced several important results. Reflection high energy electron diffraction, photoluminescence (PL) and electrical characterization were used to optimize the MBE growth. Optimized pn junctions exhibit record carrier lifetimes on the order of several tenths of a microsecond. The surface Fermi level of InAs previously had been thought to be pinned in the conduction band, thereby creating an inversion layer on the surface of p-type InAs. If this were true, the sidewalls of pn mesas would short out the junction, creating large reverse leakage currents. The present work suggests that this picture of InAs's surface Fermi level may not be accurate. InAs pn junctions with excellent I-V characteristics have been measured. PN junctions produced reverse leakage currents as low as 0.05 A/cm<sup>2</sup>. The critical thickness for cracking of tensile-strained Al<sub>x</sub>In<sub>1-x</sub>As on InAs was experimentally determined. Low Al compositions (x~7%) ex-

hibit critical thicknesses of  $\sim 600 \text{ \AA}$ . Larger Al compositions ( $x \sim 40\%$ ) produce smaller critical thickness, around  $35 \text{ \AA}$ . Doping limitation characteristics of silicon and beryllium in InAs were also investigated. Silicon doping produces poor electrical behavior and reduces PL efficiency. P-type doping with beryllium exhibits a hole density limit of approximately  $1 \times 10^{19} \text{ cm}^{-3}$  under normal growth conditions. However, low temperature growth of InAs:Be increases the maximum achievable hole concentration by an order of magnitude. Three types of InAs transistors were investigated: bipolar junction (homojunction) transistors (BJT's), heterojunction bipolar transistors (HBT's) and tunneling emitter bipolar transistors (TEBT's).  $\text{Al}_x\text{In}_{1-x}\text{As}$  was used in the HBT and TEBT devices. BJT and HBT devices exhibit common emitter current gains of  $\sim 100$ . The use of the wide-gap AlInAs emitter in the HBT doubles the current gain, relative to a comparable BJT. NPN and pnp TEBT studies show that the majority of the band discontinuity of  $\text{Al}_x\text{In}_{1-x}\text{As}/\text{InAs}$  lies in the conduction band of the heterojunction. This work was supported by DARPA and ONR (C. E.C. Wood), NSF and the AFRL Palace Knight Program.

### 3:40 PM

**Z2, Reproducible Growth of AlInAs/InGaAs HBTs by MBE Using a Mathematical Growth-Rate Model:** *B. Shi*<sup>1</sup>; M. Sawins<sup>1</sup>; A. Arthur<sup>1</sup>; S. Thomas, III<sup>1</sup>; C. Fields<sup>1</sup>; T. Hussain<sup>1</sup>; M. Sokolich<sup>1</sup>; <sup>1</sup>HRL Laboratories, LLC., Microelect. Lab., 3011 Malibu Canyon Rd., Malibu, CA 90265 USA

Beryllium (Be) is commonly used for p-type doping of InGaAs by molecular beam epitaxy (MBE) because of its high doping efficiency in InGaAs and its compatibility with MBE systems. High base doping ( $> 3 \times 10^{19} \text{ cm}^{-3}$ ) is needed in order to make high-speed heterojunction bipolar transistors (HBTs) by boosting  $f_{\text{max}}$ , lowering the extent of base current crowding and shortening the electron base-transit time. However, because of the bonding free-energy issues involved, when the Be flux impinging on a growing layer is high, the amount of Be incorporated into the lattice is very sensitive to the growth surface temperature. Absorption-edge spectroscopy (ABES) can be used to monitor the substrate temperature to eliminate the temperature control uncertainty associated with the variation in InP substrate backside polish. With a fixed ABES substrate temperature, the surface temperature depends on epitaxial InGaAs collector and subcollector thickness and compositions because of a distortion in the spectral shape of the substrate transmission spectrum due to the absorption of light in the narrow-bandgap InGaAs. In this work, group-III furnace temperature settings are determined using a mathematical model to maintain run-to-run source flux reproducibility. The mathematical model solves mass-conservation differential equations to predict growth rates by taking into account the effect of growth source depletion on the growth rate. With the model guiding daily AlInAs/InGaAs HBT growth, the InGaAs layer thickness and composition are within  $\pm 0.1\%$  and  $\pm 1.7\%$ , respectively, of the targeted values. Figure 1 shows the percentage of the measured In fraction off from the predicted (i.e., the desired) one in the InGaAs ternary layer as a function of the In-crucible use time since a time when the InGaAs growth rate and composition were calibrated. Such a precise epitaxy of InGaAs has resulted in an excellent MBE reproducibility of AlInAs/InGaAs HBTs. Figure 2 displays measured base sheet resistance as percentage of the average base sheet resistance value from the wafers which have been processed so far out of fifty consecutive runs. 95% of the data points lie between 97% and 103% of the average value.

### 4:00 PM

**Z3, Tunable Mid-Infrared Photodetectors Made of  $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{Al}_y\text{Ga}_{1-y}\text{As}/\text{Al}_z\text{Ga}_{1-z}\text{As}$  Asymmetric Step Quantum-Well Structure:** *Wengang Wu*<sup>1</sup>; <sup>1</sup>Peking University, Dept. of Compu. Sci. & Tech., Inst. of Microelect., Beijing 100871 China

Tunable mid-infrared ( $3\sim 5.3 \mu\text{m}$ ) photodetectors are made of an optimized  $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{Al}_y\text{Ga}_{1-y}\text{As}/\text{Al}_z\text{Ga}_{1-z}\text{As}$  asymmetric step quantum-well structure grown with MBE on a semi-insulating (100) GaAs substrate. The fabrication of the components was processed out of the grown wafer by using the standard photolithographic and III-V wet chemical etching technologies. The detectors display photovoltaic-type photocurrent response as well as applied bias-tunable peak wavelength of the main response, which is ascribed to the Stark shifts of the intersubband transitions from the local ground states to the extended first excited states in the quantum wells, at the  $3\sim 5.3 \mu\text{m}$  infrared atmospheric transmission window. The photovoltaic mode operation of the detectors is proved experimentally due to the built-in electric field existing in the active multi-quantum well region. The blackbody receptivity of the detectors reaches

to about  $1.0 \times 10^{10} \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$  at 77K under bias of  $\pm 7 \text{ V}$ . Not only high blackbody receptivity but also strong photocurrent response, which have approached to the application requirements actually, can be achieved when the fabricated mid-infrared receiving detectors operate under relatively large positive bias or relatively small negative bias. The theoretical analysis on the property of bias-controlled tunable main photoresponse peak position of the detectors, which was made by the method of expanding the electron wave function in terms of normalized plane wave basis within the framework of the effective-mass envelope-function theory, agree well with the corresponding experimental measurements.

### 4:20 PM Student

**Z4, Growth and Properties of AlGaInP Laser Diodes Grown on GaAs and Ge Substrates by Solid Source Molecular Beam Epitaxy:** *Ojin Kwon*<sup>1</sup>; Carrie L. Andre<sup>1</sup>; Steven Ringel<sup>2</sup>; <sup>1</sup>Ohio State University, Electl. Eng., 2015 Neil Ave. Columbus, OH 43210 USA; <sup>2</sup>Ohio State University, Electl. Eng. Dept., 2015 Neil Ave., 205 DL, Columbus, OH 43210-1275 USA

$(\text{Al}_x\text{Ga}_{1-x})_{.51}\text{In}_{.49}\text{P}$  based visible laser diodes (LD) operating in the 600nm band are receiving considerable attention for applications such as optical recording, plastic fiber-optic communication, laser printing, solid-state laser pumping, and as substitutes for HeNe laser and AlGaAs based laser diodes. Most of these materials have been studied via growth techniques that use hydride gases to accommodate P sources. Recently, valved solid phosphorus cracker sources have been developed that eliminate the flux instability and switching problems associated with conventional GaP effusion phosphorus sources, thus allowing high quality phosphide alloy growth using solid source molecular beam epitaxy (SSMBE). This paper explores growth properties and device characteristics of single quantum well (SQW)  $(\text{Al}_x\text{Ga}_{1-x})_{.51}\text{In}_{.49}\text{P}$  based laser diodes (LD) grown on GaAs and Ge substrates using SSMBE, where a valved cracker P source has been used. III-V epitaxy on Ge substrates is of interest in field of high efficiency photovoltaics. Moreover, the small mismatch between GaAs and Ge can allow optoelectronic devices on Ge substrates, and this feature can be further extended to monolithic integration with Si microelectronics via SiGe step graded buffers. In order to examine optimum growth conditions for the  $\text{Ga}_{.51}\text{In}_{.49}\text{P}$  active layer, X-ray diffraction and photoluminescence (PL) have been performed on various samples grown under different group III/P flux ratios at a pre-optimized growth temperature, 490C. Less than 1% composition error from the target was confirmed from X-ray analysis and the  $\text{Ga}_{.51}\text{In}_{.49}\text{P}$  sample grown at 1/7 flux ratio generates the highest PL intensity. For the cladding layer, indirect gap  $\text{Al}_{1.5}\text{In}_{.49}\text{P}$  (2.35eV) is used to achieve maximum optical confinement instead of the conventional direct gap  $(\text{Al}_{1.7}\text{Ga}_{.3})_{.51}\text{In}_{.49}\text{P}$  (2.3eV). To increase the conduction band offset, attempts to maximize the p-doping of  $\text{Al}_{1.5}\text{In}_{.49}\text{P}$  were made. A maximum of  $8.07 \times 10^{17} / \text{cm}^3$  was obtained as confirmed by Hall measurement.  $(\text{Al}_{1.5}\text{Ga}_{.5})_{.51}\text{In}_{.49}\text{P}$  was used for the separate confinement heterostructure (SCH) layer to improve conduction band offset instead of  $(\text{Al}_{1.6}\text{Ga}_{.4})_{.51}\text{In}_{.49}\text{P}$  that is typically used as a SCH layer. Due to a limited number of group III effusion cells and to obtain exact composition, the quaternary AlGaInP layers were grown using a digital alloy approach consisting of alternating  $\text{Ga}_{.51}\text{In}_{.49}\text{P}$  and  $\text{Al}_{1.5}\text{In}_{.49}\text{P}$  layers by switching Ga and Al shutters under fixed In rate. This approach is advantageous since precise compositions can be obtained without adjusting cell temperatures at a growth-stop where non-radiative defects can accumulate. X-ray analysis showed a digitally alloyed 4000A unintentionally doped  $(\text{Al}_{1.5}\text{Ga}_{.5})_{.51}\text{In}_{.49}\text{P}$  film grown on GaAs substrate is lattice matched to the GaAs substrate and low temperature PL confirmed a band gap of 2.223eV at 18K. Two identical LD structures have been grown on GaAs and Ge substrates that included  $1 \mu\text{m}$  thick  $\text{Al}_{1.5}\text{In}_{.49}\text{P}$  cladding/1300A  $(\text{Al}_{1.5}\text{Ga}_{.5})_{.51}\text{In}_{.49}\text{P}$  SCH/80A GaInP SQW active layer. Visible spontaneous red emission below 50mA was observed from test LD bars grown on GaAs substrates, consisting of 10 arrays having dimension of  $5 \mu\text{m}$  waveguide width x  $1000 \mu\text{m}$  cavity length. Room temperature PL of GaAs LD samples displayed a peak wavelength of 647nm. Detailed device characteristics including light intensity vs. current of AlGaInP LDs grown on both GaAs and Ge substrates will be presented, and a comparison between digitally alloyed and non-digitally alloyed  $(\text{Al}_{1.5}\text{Ga}_{.5})_{.51}\text{In}_{.49}\text{P}$  films will be discussed using X-ray analysis and low temperature PL.

### 4:40 PM

**Z5, Negative Differential Resistance of  $\text{CdF}_2/\text{CaF}_2$  Resonant Tunneling Diode Grown on Si(100) Substrate Using Nanoarea Local Epitaxy:** *Masahiro Watanabe*<sup>1</sup>; Tatsuya Ishikawa<sup>1</sup>; Masaki Matsuda<sup>1</sup>; Tohru

Kanazawa<sup>1</sup>; Masahiro Asada<sup>1</sup>; <sup>1</sup>Tokyo Institute of Technology, Dept. of Info. Proc., 4259 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa 226-8502 Japan

CdF<sub>2</sub>/CaF<sub>2</sub> heterostructure is an attractive candidate for quantum devices on Si substrate such as resonant tunneling diodes and quantum intersubband transition devices because of its large conduction band discontinuity ( $\Delta E_c \sim 2.9\text{eV}$ ) at the heterointerface. Due to the large  $\Delta E_c$  and wide band gap energy of CdF<sub>2</sub> ( $E_g \sim 8\text{eV}$ ) and CaF<sub>2</sub> ( $E_g \sim 12\text{eV}$ ), resonant tunneling diodes (RTD) using CdF<sub>2</sub>/CaF<sub>2</sub> heterostructures are expected to show negative differential resistance (NDR) characteristics with extremely large peak to valley ratio (PVR) because of the small valley current even at room temperature. CdF<sub>2</sub> and CaF<sub>2</sub> have fluorite lattice structure and well lattice matched to Si with mismatches of -0.8%, +0.6% at room temperature, respectively. Recently, we have reported high peak-to-valley current ratio of double barrier CdF<sub>2</sub>/CaF<sub>2</sub> RTD grown on Si(111) substrate. In this study, we report epitaxial growth and room temperature NDR of CdF<sub>2</sub>/CaF<sub>2</sub> double barrier RTD on Si(100) substrate for the first time using Nanoarea Local Epitaxy and hydrogen terminated Si(100). N-type Si(100) substrate with 0.1° miscut was chemically cleaned and 15nm-thick SiO<sub>2</sub> layer was formed by dry oxidation. Subsequently, SiO<sub>2</sub> holes of 100-400nm-diameter were formed by electron beam lithography and wet chemical etching by 50% HF solution at room temperature, which yielded atomically flat hydrogen terminated Si(100) surfaces. After loaded into the ultra-high vacuum chamber, 1nm-thick CaF<sub>2</sub> was grown at 300°C, with ionization by electron bombardment without acceleration, which leads atomically flat CaF<sub>2</sub> epilayer instead of 3D island formation. Hydrogen terminated Si surfaces can effectively suppress anisotropic migration of CaF<sub>2</sub> due to Si dimer array on Si(100) atomic terraces. On the first 1nm-thick CaF<sub>2</sub> barrier layer, 1.9nm-thick CdF<sub>2</sub> quantum well layer was grown at 80°C. After the growth, the top 1nm-thick CaF<sub>2</sub> barrier layer was grown at 80°C with ionization. Au/Al electrode of 100μm-square was evaporated on the array of double barrier RTDs grown in SiO<sub>2</sub> holes. In the measurement of current-voltage characteristics, clear room temperature NDR was observed and typical peak-to-valley current ratio was 4. To our knowledge, this is the first demonstration of room temperature NDR using fluorite based heterostructures on Si(100) substrate. This work was supported by PREST-JST, and the Ministry of Education, Culture, Sports, Science and Technology through a Scientific Grant-in-Aid.

## Session AA: Nanoscale Fabrication and Self-Assembly

Thursday PM      Room: Corwin West  
June 27, 2002      Location: University of California

*Session Chairs:* Supriyo Bandyopadhyay, University of Nebraska-Lincoln, Dept. of Electl. Eng., Lincoln, NE 68588-0511 USA; David Janes, Purdue University, Dept. of Elect. Eng., 1285 Electl. Eng. Bldg., W. Lafayette, IN 47907-1285 USA

### 1:20 PM Student

**AA1, Template-Driven PECVD-Deposited Dielectric Tubules for Nano-Electronic Applications:** James B. Mattzela<sup>1</sup>; Ludmil Zambov<sup>2</sup>; Marco A. Cabassi<sup>2</sup>; Adriana Zambova<sup>2</sup>; Theresa S. Mayer<sup>2</sup>; <sup>1</sup>Pennsylvania State University, Inter-College Prog. in Matls. Sci. & Eng., University Park, PA 16802 USA; <sup>2</sup>Pennsylvania State University, Dept of Electl. Eng., University Park, PA 16802 USA

Current methods of template-based synthesis for nanometer-scale building blocks such as nanowires and nanotubes have resulted in significant contributions to the overall development of advanced nanotechnologies. These advances have aided in the progression of traditional electronic technologies and in the growth of non-traditional technologies such as molecular electronics. Nanowire-based technologies would benefit greatly from the possibility of dielectric coatings. Dielectric coatings would provide electrical isolation between adjacent nano-devices allowing even further scaling capabilities as well as providing protection for possible imbedded molecular layers from harmful

processing procedures. Recent progress in nanoscale chemical vapor deposition (CVD) using nano-templates such as polycarbonate or alumina membranes has resulted in formation of various nanotube structures. Dielectric nanotubes (SiO<sub>x</sub> Si<sub>x</sub>N<sub>y</sub>) were fabricated using both commercially available alumina filter membranes (200nm diameter pores) and custom-made chemically anodized porous alumina membranes (sub-120nm diameter pores) as the template. Using a pulsed plasma-enhanced chemical vapor deposition (PECVD) technique whereby the reagents are evacuated and re-mixed between pulses of power, SiO<sub>x</sub> nanotubes have been created from a binary gas system of silane and oxygen (SiH<sub>4</sub>-O<sub>2</sub>). Si<sub>x</sub>N<sub>y</sub> nanotubes can be made by the same PECVD technique (using binary system of SiH<sub>4</sub>-N<sub>2</sub> as the source gases) as well as by a simple low-pressure chemical vapor deposition (LPCVD) technique (using dichlorosilane-ammonia-nitrogen as the source/carrier gases) where the gases are flowed at low enough partial pressures to make the chemical reaction the rate limiting step instead of being limited by gas diffusion into the pores. Nanotubes were characterized qualitatively by approximating the thickness of the film by ellipsometry on control samples present in the chamber during deposition and using secondary electron microscopy (SEM) to verify that the nanotubes were hollow. Quantitative measures of the dielectric properties were made by SEM measurement of the length of the tubules in the membranes, by transmission electron microscopy (TEM) measurement of the dielectric thickness on gold nanorods, and electrical leakage current measurements through the dielectric after electro-fluidic alignment of the gold nanorod structure onto a test substrate and metallization of electrical contacts.

### 1:40 PM Student

**AA2, Selective Molecular Beam Epitaxial Growth of InAs Dots on Nanoscale-Patterned SiO<sub>2</sub>/GaAs(001):** S. C. Lee<sup>1</sup>; L. R. Dawson<sup>1</sup>; K. J. Malloy<sup>1</sup>; S. R. Brueck<sup>1</sup>; <sup>1</sup>University of New Mexico, Ctr. for High Tech. Matls., 1313 Goddard SE, Albuquerque, NM 87106 USA

Growth of InAs dots by molecular beam epitaxy (MBE) within spatially confined ~ 100-nm scale circular holes patterned on SiO<sub>2</sub>/GaAs(001) is reported. A two-dimensional, 285-nm period circular hole pattern was generated in 80-nm thick SiO<sub>2</sub> film on GaAs(001) by large-area interferometric lithography and dry etching. Deposition of InAs corresponding to a 10-nm thick layer was performed at a growth temperature of 535°C and a growth rate of 0.1 ML/s where a very-low sticking coefficient of In atoms on the SiO<sub>2</sub> surface results in selective growth on the exposed GaAs surface. Unlike growth of self-assembled InAs quantum dots (QDs) on an unpatterned GaAs surface for which a Stranski-Krastanov (S-K) wetting layer plays a crucial role, this nanoscale patterned selective growth proceeds with only a limited wetting layer area allowed by each hole opening in the SiO<sub>2</sub> mask. Formation of spherical-section single InAs dots of height of 10-15nm, filling each hole of diameter of about 50 to 100nm without a wetting layer extending beyond a hole area, was observed using scanning electron microscopy and atomic force microscopy. A transition from single- to multiple-dot formation occurs at hole diameters of ~100 to 150nm. Isolated, self-assembled QDs as well as partially coalesced multi-dot regions were observed in ~200-nm diameter and larger holes. The reported lateral dimension and density of self-assembled InAs QDs grown on unpatterned GaAs(001) at 535°C are greater than 30nm and about 1.5x10<sup>10</sup> cm<sup>-2</sup>, respectively. Thus, the average area allocated to a single QD is about 80 x 80 nm<sup>2</sup> and its lateral scale is comparable to the observed transition diameter between single- and multi-dot behavior. This comparison indirectly supports the interpretation of single-dot formation for hole of diameter less than 100nm. Therefore, these experiments provide important insight into the mechanisms of S-K growth and the interplay between the area of the wetting layer and the formation of the dots. Also, extended to somewhat smaller hole patterns, they offer the possibility of three dimensional customization of QD shape and size at high uniformity and with precise positioning.

### 2:00 PM Student

**AA3, Fabrication of Cobalt Silicide/Silicon Nanowires:** Ahmad M. Mohammad<sup>1</sup>; Suzanne E. Mohney<sup>1</sup>; Kok K. Lew<sup>1</sup>; Joan M. Redwing<sup>1</sup>; Timothy E. Bogart<sup>1</sup>; Soham Dey<sup>1</sup>; <sup>1</sup>Pennsylvania State University, Matls. Sci. & Eng. 206-A Steidle Bldg., University Park, PA 16802 USA

Semiconductor nanowires have generated tremendous interest in recent years and are expected to serve as building blocks for a variety of nanoelectronic devices. For many of these devices to reach their potential, ohmic contacts to the nanowires will be required. The new geometry of the nanocontacts and their reduced length scale will undoubtedly

influence current transport as well as interfacial reactions between the metal and the semiconductor, particularly for the smallest wires, so we do not necessarily expect to be able to simply adopt conventional ohmic contact technologies for the nanowires. Lew et al. have recently fabricated single crystal Si nanowires within nanoporous templates using the vapor-liquid-solid (VLS) growth mechanism. In this abstract, we describe the successful integration of contact metal into this synthesis scheme, the fabrication of metal/semiconductor nanowires for nanocontact studies, and our plans for continued research. We have fabricated cobalt silicide nanocontacts to Si nanowires. We used nanoporous anodized alumina membranes with nominal 200nm diameter pores as templates for the nanowire growth. Silver was sputter deposited on one side of the membrane to provide a conductive layer for electrodeposition within the pores. Silver, Co and Au were then sequentially electroplated within the pores. The electroplated Ag layer inside the membrane was used to control the position of the Co and Au layers. The Au was added to participate in the vapor-liquid-solid (VLS) growth of the Si nanowires. The template was next placed in an ambient containing a 5% mixture of silane in hydrogen at 500°C, and Si nanowires were grown by the VLS mechanism. At this temperature, the Si nanowires also reacted with the Co portion of the nanowire to form a cobalt silicide. After growth, the nanowires were released from the membranes using 8.0 M nitric acid to etch away the Ag and 1.0 M sodium hydroxide to remove the alumina membrane. Scanning electron microscopy and energy dispersive spectroscopy were used to examine the multilayer nanowires. We found that all of the Au within the membrane moved along the growing tip of the Si nanowire during the VLS growth process, leaving the other end of the Si portion of the nanowire in direct contact with cobalt silicide. Transmission electron microscopy is now underway to identify which cobalt silicide is in contact with Si and to study the influence of the cobalt silicide on the crystalline quality of the Si nanowire. Measurements of electrical transport in the nanowires and through the nanocontacts are planned, and we expect to be able to adapt our fabrication process to synthesize other metal silicide/Si nanowires for nanocontact studies.

#### 2:20 PM Student

**AA4, Growth Characteristics of Silicon Nanowires Synthesized by Vapor-Liquid-Solid Growth in Nanoporous Membranes:** *Kok-Keong Lew<sup>1</sup>*; Timothy E. Bogart<sup>1</sup>; Joan M. Redwing<sup>1</sup>; <sup>1</sup>Pennsylvania State University, Dept. of Mats. Sci. & Eng., 5 Hosler Bldg., University Park, PA 16802 USA

There is growing interest in the use of the vapor-liquid-solid (VLS) growth for the fabrication of semiconductor nanowires with controlled diameters, aspect ratios and physical characteristics that may serve as the basis for future nanoscale device technologies. We have previously described the use of nanoporous alumina membranes as templates for the VLS growth of silicon nanowires. The fabrication process began with electrodeposition of a thin segment of Au into the membrane pores to serve as a catalyst for VLS growth. Silane was employed as the Si source, which diffused into the pores to react with Au at 500°C resulting in Si nanowire growth within the membrane. In this method, the nominal pore size of the membrane defines the diameter of the nanowires which can be varied over the range from 10nm to 200nm. The alumina membrane also serves as a convenient platform by which to study the effect of process conditions on Si nanowire growth. In this study, we have investigated the effect of growth temperature (400-600°C), SiH<sub>4</sub> partial pressure (0.13-0.65 Torr) and Au thickness (0.14-0.75 μm) on the growth rate and structural properties of Si nanowires. The total pressure of the reactor was held constant at 13 Torr in all the experiments. Commercially available alumina membranes with a nominal pore diameter of 200nm were used for a portion of the experiments. Alumina membranes with smaller pore diameters (~ 100 nm) were also prepared through anodization of aluminum plate at constant cell potential in oxalic acid (C<sub>2</sub>H<sub>2</sub>O<sub>4</sub>). The length of Si nanowires increased linearly with growth time over the temperature range from 400-500°C. The measured nanowire growth rates were 0.15 μm/min at 400°C and 1.0 μm/min at 500°C. At temperature greater than 500°C, Si was observed to deposit on the surface of the membrane thereby blocking the pores and reducing the nanowire growth rate. Analysis of the nanowire growth rate versus temperature data results in an activation energy of approximately 21 kcal mol<sup>-1</sup> for the process. The smaller activation energy compared to that of conventional low-pressure chemical vapor deposition of Si is ascribed to the existence of catalytic Au. The growth rate of the Si nanowires was found to decrease

with an increase in the thickness of the Au segment. Scanning electron microscopy analysis of the nanowires revealed that very thin Au segments lead to non-uniform wire diameters, which could contribute to the higher growth rate. The effect of SiH<sub>4</sub> partial pressure on the growth of Si nanowires was also investigated. The growth rate of the nanowires was found to be nonlinearly proportional to SiH<sub>4</sub> partial pressure. A possible mechanism of Si nanowire growth in the framework of two-step heterogeneous reaction model is discussed.

#### 2:40 PM Student

**AA5, Structural and Optical Properties of Vertically Well-Aligned ZnO Nanorods Grown by Metalorganic Vapor Phase Epitaxy:** *W. I. Park<sup>1</sup>*; D. H. Kim<sup>1</sup>; M. S. Kim<sup>1</sup>; G. C. Yi<sup>1</sup>; <sup>1</sup>Pohang University of Science and Technology, Mats. Sci. & Eng., San 31, Hyoja Dong, Nam-ku, Pohang 790-784 S. Korea

One-dimensional (1D) nanostructures, such as nanowires, nanorods, and carbon nanotubes (NTs), offer great potential as building blocks for applications in nanoelectronics and photonics due to its high aspect ratio as well as the specific semiconducting behavior. For semiconductor nanowires and nanorods in contrast to carbon nanotubes, doping and bandgap controls seem to be much easier, which enable to fabricate hetero nanostructures. Hence, diverse materials such as Si, Ge, GaAs, InP, ZnO, and GaN have been synthesized to the form of nanowires or/and nanorods and a catalysis-assisted vapor-liquid-solid (VLS) growth method has been employed for the nanostructures growth. In VLS growth, impurities act as catalysts and play an essential role in forming liquid alloy droplets for deposition on a preferred site. During the catalysis-assisted growth, however, the metal catalyst might be incorporated as an impurity into nanomaterials, and generate unintentional defect levels. Since even low defect concentrations affect physical properties of semiconductors, unintentionally doped impurities are detrimental to device fabrications. In this presentation, we demonstrate MOVPE growth of ZnO nanorods without employing any metal catalysts usually needed in other methods. The nanorods were grown on Al<sub>2</sub>O<sub>3</sub> (0001) substrates using MOVPE. Field emission scanning electron microscopy (FE-SEM) clearly revealed that nanorods with uniform distributions in their diameters, lengths, and densities were grown vertically from the substrates. The mean diameters and lengths are ~25nm and 800nm, respectively. In addition, X-ray diffraction measurements also exhibited that ZnO nanorods were grown epitaxially with homogeneous in-plane alignment as well as a c-axis orientation. Furthermore, high-resolution transmission electron microscopy showed that the nanorods are single-crystalline and dislocation-free. The optical properties of ZnO nanorods were investigated by photoluminescence (PL) spectroscopy. At room temperature, the dominant peak was observed at 3.29 eV, which is attributed to the free exciton peak. Meanwhile, the deep level green emission associated with point defects commonly observed in ZnO epilayers was found to be extremely weak. The strong and sharp excitonic emission and low deep level emission indicate that the ZnO nanorods are of excellent optical quality, comparable to the ZnO epilayers. Furthermore, temperature-dependent PL properties of ZnO nanorods will be discussed.

#### 3:00 PM Break

#### 3:20 PM Student

**AA6, Selective Electric-Field Assembly of Metallic Nanowires:** *Baharak Razavi<sup>1</sup>*; Benjamin R. Martin<sup>2</sup>; Sarah K. St. Angelo<sup>2</sup>; Thomas E. Mallouk<sup>2</sup>; Thomas N. Jackson<sup>3</sup>; <sup>1</sup>Philips Semiconductor, Zurich, Switzerland; <sup>2</sup>Pennsylvania State University, Chem., 152 Davey Lab., University Park, PA 16802 USA; <sup>3</sup>Pennsylvania State University, Electl. Eng., 216 EE W. Bldg., University Park, PA 16802 USA

Nanostructures and assemblies of nanocomponents are of increasing interest for a variety of current and future applications. A number of techniques have been proposed and demonstrated for nanocomponent assembly. Electric-field assembly is of particular interest as an alignment technique because it can be used to rapidly and precisely align large numbers of nanocomponents. We report here on progress using near-field forces to selectively position gold nanowires suspended in solution between electrodes. We demonstrate electrode-selective electric-field-assisted assembly of a nanowires and multiple-step electric-field assembly for sequentially aligning nanowires. Multiple-step electric-field assembly is accomplished by varying the near-field forces in the vicinity of the alignment electrodes such that nanowires align to the electrodes with the largest near-field force, then to electrodes with smaller forces. To

further improve the alignment process we have designed a fluid cell to contain the nanowire suspension fluid during alignment, thus avoiding problems related to solution evaporation and related meniscus forces. Gold nanowires suspended in solution were synthesized using a process described previously. In this work we use two simple approaches to achieve selective alignment of gold nanowires. In the first approach the coupling capacitance between the alignment electrodes and the underlying busbars is varied while the shape of the alignment electrodes (inter-electrode gap) is kept constant. Since the potential between the alignment electrodes is largest for the electrodes and busbars with the largest coupling capacitance, nanowires are positioned at these electrodes at a lower applied alignment voltage than for electrodes and busbars with smaller coupling capacitance. The same selectivity is achieved when the gap between alignment electrodes is varied for electrodes and busbars with equal coupling capacitance. The fraction of the applied alignment voltage that drops between the two alignment electrodes has been calculated as a function of frequency for different coupling capacitance. At a fixed alignment frequency the voltage drop between alignment electrodes with different coupling capacitance is largest for the electrodes with the largest coupling capacitance and is the controlling factor for selective alignment. It is also shown that at higher frequencies the voltage needed to drive alignment is lower. Using either selective alignment approach other nanowires can be subsequently aligned to vacant alignment electrodes by increasing the alignment potential. Additionally, this technique can be easily extended to a range of nanocomponents or other fluid suspended objects for multiple-step assembly of more complex objects.

### 3:40 PM

**AA7, Preferred Crystallographic Orientations and Coercivity Mechanism in Self-Ordered Ferromagnetic Nanowires by AC Electroforming:** K. H. Lee<sup>1</sup>; H. Y. Lee<sup>1</sup>; W. Y. Jeung<sup>1</sup>; W. Y. Lee<sup>1</sup>; <sup>1</sup>Korea Institute of Science & Technology, Seoul 136-791 S. Korea

We have investigated the crystal structures and magnetic properties of  $\alpha$ -Fe and  $\text{Fe}_{21}\text{Ni}_{79}$  nanowire arrays fabricated by AC electroforming into self-ordered nanosized pores in anodic aluminum oxide (AAO). The nanopores were found to have diameters of 5-100nm and aspect ratios of 300-1000, depending on the anodization conditions. The subsequent AC electroforming was carried out at 15 V and 50 Hz using a modified Watt's nickel bath containing iron sulfate and ascorbic acid, giving rise to clear and uniform  $\alpha$ -Fe and  $\text{Fe}_{21}\text{Ni}_{79}$  nanowires. X-ray diffraction patterns provide direct experimental evidence that the  $\alpha$ -Fe and  $\text{Fe}_{21}\text{Ni}_{79}$  nanowires have preferred crystallographic orientations, indicating that those were electroformed in the (211) and the (220) orientations, respectively. These results support the view that each  $\alpha$ -Fe nanowire consists of numerous single crystals and has perfect orientation, as reported in previous study using TEM and Mössbauer. By contrast, the preferred orientation of the  $\text{Fe}_{21}\text{Ni}_{79}$  nanowires is incompatible with previous work, where electrodeposited  $\text{Fe}_{21}\text{Ni}_{79}$  has no preferred orientation. It is observed that the  $\alpha$ -Fe and  $\text{Fe}_{21}\text{Ni}_{79}$  nanowires show a magnetic anisotropy with an easy axis perpendicular to the AAO film and parallel to the axis of the nanowires. For the  $\alpha$ -Fe ( $\text{Fe}_{21}\text{Ni}_{79}$ ) nanowires, coercivity  $H_c$  and squareness  $M_r/M_S$  were found to be  $\sim 2.02$  ( $\sim 1.10$ ) kOe and  $\sim 0.9$  ( $\sim 0.99$ ), respectively. According to a "chain-of-spheres" model, the coercivity in the  $\alpha$ -Fe nanowires is calculated to be 2.36 kOe, which is in good agreement with our value, demonstrating that the coercivity mechanism in the  $\alpha$ -Fe nanowires follows fanning rather than curling showing higher value ( $H_c$  4.61 kOe). Our XRD results imply that an  $\alpha$ -Fe nanowire is likely to be a long chain of single crystals or, more specifically, "bamboo-like structure" with the (211) preferred orientation. We also found that thermal anneal is effective to improve coercivity in ferromagnetic nanowires. Our results illustrate the possibility of fabricating ideally self-ordered ferromagnetic nanowire arrays based on the AAO templates, opening an opportunity towards a new class of ultrahigh density magnetic recording media.

### 4:00 PM

**AA8, Self-Assembled InAs/InP Nanostructures:** Humberto R. Gutiérrez<sup>1</sup>; Mônica A. Cotta<sup>1</sup>; Mauro M.G. de Carvalho<sup>1</sup>; <sup>1</sup>Unicamp, DFA/LPD, Instituto de Física Gleb Wataghin, Campinas, São Paulo 13081-970 Brazil

InAs nanostructures in an InP matrix have received much attention in the last years. Recently, we have reported the conditions that determine the InAs shape transition—from wires to dots—for films grown on (100) InP substrates by Chemical Beam Epitaxy. We have obtained intermedi-

ary states containing both wires and dots in the same sample. However, the grown of such self-assembled nanostructures requires a complete understanding and control of the formation mechanisms. In this sense we have obtained a complete picture of the InAs nanostructures formation. InAs growth evolution was monitored by Reflection High Energy Electron Diffraction (RHEED). The samples were analyzed by Atomic Force Microscopy (AFM), High Resolution Transmission Electron Microscopy (HRTEM) and Photoluminescence (PL). The influence of the temperature, growth rate and the InAs thickness on the wires formation was studied. For the lower growth rates used here and InAs thicknesses up to three monolayers, the wires run quite uniformly along the [0-11] direction with width in the range 15-40nm, depending on growth conditions. For high growth rates the wires are not well defined while deposition of four InAs monolayers makes the wires shorter and wider. On the other hand the wires are not observed when InAs is formed only by As-P exchange. The temperature is also determinant in the wire formation. For low growth temperatures no quantum wires appear in the AFM measurements. The InAs wires formation begins for intermediary temperatures. The homogeneity of the wires increases with the temperature. For temperatures close to 530°C there is a blue shift in the PL signal that could be produced by the P/As exchange at the film-substrate interface. RHEED measurements show that the formation of chevron streaks along the [1-10] direction occurs for a limited temperature range. This indicates that the facet stability strongly depends on the temperature. Our results suggest that the wires are a metastable shape originated by the anisotropic diffusion over the InP buffer layer during the formation of the first InAs monolayer. This kinetically controlled process occurs in a well-defined range of growth conditions, which determine the distribution, homogeneity and shape of the resulting nanostructures.

### 4:20 PM

**AA9, Late News**

### 4:40 PM

**AA10, Nanofabrication and Magneto-Characterization of One-Dimensional Quantum Channels in InAs/AlSb:** C. H. Yang<sup>1</sup>; M. J. Yang<sup>2</sup>; K. A. Cheng<sup>1</sup>; J. C. Culbertson<sup>2</sup>; <sup>1</sup>University of Maryland College Park, Electl. & Compu. Eng., Rm. 1323, College Park, MD 20742 USA; <sup>2</sup>Naval Research Laboratory, ESTD, Washington, DC 20375 USA

We report a novel technique for nanodevice fabrication in the InAs/AlSb 6.1Å material system that utilizes the large difference in the surface Fermi level pinning positions of InAs (E<sub>f</sub>(InAs)) and that of AlSb. A high mobility InAs/AlSb single quantum well is capped with a 3nm, intentionally p-type InAs layer. As a result of its structure and a relatively low E<sub>f</sub>(InAs) there are no free carriers in the InAs quantum well, making the quantum well insulating as-grown. Simply by selectively removing the 3nm thin p-doped InAs cap layer with a wet etch, the surface Fermi level becomes pinned on AlSb and shifts upward by half an electron volt. This results in a drastic change in band bending and creates a conducting electron channel in the buried InAs quantum well. We demonstrate with experiment and the support of a self-consistent band bending calculation that this scheme is highly effective for nanofabrication. We have also performed systematic magnetoresistance measurements on InAs nanometer wires and rings fabricated by this novel scheme. Based on studies with various wire widths down to 80nm and lengths down to 400nm, we found that the lateral confinement leads to predominately specular boundary scattering, and as a result the elastic mean free path is not substantially degraded when the system is patterned into nanometer-wide quantum wires. In addition, the lateral electrostatic potential profile is found to be abrupt, and the conducting channel width is approximately the width defined by lithography. A number of ballistic transport phenomena are observed in the Hall bar geometry at 4K, including the quenching of the Hall resistance, the last Hall plateau, and a negative bend resistance. Their dependence on the magnetic field indicates a relatively sharp corner in the cross junction. Quantum phenomena such as magnetic depopulation of 1D sublevels and universal conductance fluctuations are also observed in InAs wires. In ring geometry, we have observed Aharonov-Bohm interference that exhibits characteristics different from those of the GaAs counterpart due to the ballistic nature of electron transport and the narrowness of the one-dimensional conducting channel width.

## Session BB: Porous Semiconductors: Fabrication, Properties, and Applications

Thursday PM      Room: Corwin East  
June 27, 2002      Location: University of California

*Session Chairs:* Stephen E. Sadow, University of South Florida, 4202 E. Fowler Ave., ENB 118, Tampa, FL 33612 USA; Michael MacMillan, Sterling Semiconductor, Inc., 3401 Cragmont Dr., Tampa, FL 33619 USA

### 1:20 PM Student

**BB1, Characterization and Effects of Hydrogen Etching of Porous Silicon Carbide:** *Ashutosh Sagar*<sup>1</sup>; C. D. Lee<sup>1</sup>; R. M. Feenstra<sup>1</sup>; C. K. Inoki<sup>2</sup>; T. S. Kuan<sup>2</sup>; <sup>1</sup>Carnegie Mellon University, Physics, 5000 Forbes Ave., Pittsburgh, PA 15213 USA; <sup>2</sup>University at Albany, SUNY, Physics, Albany, NY 12222 USA

The morphology of porous SiC has been studied. Scanning electron microscopy (SEM), transmission electron microscopy (TEM) and x-ray scattering are used to measure the surface porosity, pore size and their distribution. In addition, hydrogen etching is used to prepare atomically flat surfaces of SiC for epitaxial growth. The effect of H-etching on surface and bulk pores has been studied. Plan view SEM images of porous SiC show surface pores of about 20-30nm in diameter with inter-pore spacing of about 100nm. Cross-sectional SEM and TEM images show that the pore formation starts with a few pores on the surface and then the porous network grows in a V-shaped branched structure below the surface. Consequently, there appears to be a thin nonporous skin layer of about 50nm on top. Measuring the pore density and average pore size from the images, we find that the porosity increases from about 2% in the skin layer to about 20% in the bulk. X-ray scattering has been used to measure the surface porosity and pore size. At grazing angles of incidence, x-rays undergo total external reflection from the surface. By measuring the critical angle for this reflection on various porous SiC surfaces, the surface porosity of about 2% seen in SEM has been confirmed. Bragg diffraction peaks from the porous SiC samples show a broad hump at the bottom of the main peak. This hump corresponds to the diffuse scattering produced by the porous structure. Bragg peaks from the nonporous samples do not show this feature and produce only a narrow peak. The diameter (D) of the scattering objects, i.e. pores, can be obtained from the FWHM of the diffused scattering part of the Bragg peak by  $D = 2\lambda/\Delta q_0$  where  $\Delta q_0$  is the FWHM in q-space. By this technique we get an average pore size of about 20nm on our samples, which is in good agreement with plan view SEM observations. Finally, effects of H-etching on the porous SiC have been studied. H-etching rates of porous and nonporous SiC are measured. It is found that the porous SiC etches faster than the nonporous SiC. Etching rates of porous SiC are temperature dependent but reach saturation above about 1650° C. Hydrogen etching increases the surface pore sizes and opens up hexagonal pores. Cross sectional SEM images show that the porous network in the bulk is affected due to annealing the sample at high temperature (~ 1700°C) during the H-etching process. X-ray reflectivity is used to measure the change in sample porosity due to H-etching as a function of etching time. This work was supported by the DURINT program administered by the Office of Naval Research under Grant N00014-0110715.

### 1:40 PM

**BB2, Array of Macro-Pores on the (100) Plane of N-Type Si Prepared by Photo-Electrochemical Etching:** *Jing-Chie Lin*<sup>1</sup>; Chih-Chang Tasi<sup>1</sup>; Chien-Ming Lai<sup>1</sup>; Wern-Dar Jehng<sup>1</sup>; Sheng-Long Lee<sup>1</sup>; <sup>1</sup>National Central University, Dept. of Mechl. Eng., No. 38, Wu-chuan Li, Chung-li, Taoyuan, 320 Taiwan

Array of macro-pores (diameter roughly at 4µm) was prepared on the (100) plane of an n-type Si wafer by photo-electrochemical etching in fluoride solution. Prior to photo-electrochemical process, a miniature array was patterned on the oxide overcoat by a sequence of lithographic process and then chemical etching by potassium hydroxide to initiate the

reverse pyramid pits. Direct current anodic potentiodynamic polarization was used in screening the possible parameters that affect the etching rate and thereby find out the optimal condition for each parameter. Resulting from a series of potentiodynamic studies, the anodic current corresponding to active and passive regions is determined by the factors in the following: the concentration of the fluoride, kinds of additive involved in the electrolyte, concentration of the additive, power of the irradiation, intensity of the irradiation, potentials selected in electrochemical reaction, etc. In preparing the macro-pores array, the photo-electrochemical dissolution was carried out potentiostatically in a TPFE electrolytic cell filled with 100 ml fluoride. The silicon wafer exposed an area of 1 cm<sup>2</sup> was used as the working electrode (anode), platinum foil with the same area as the counter electrode (cathode). A capillary made of TPFE tubing connected to saturated calomel electrode was the reference electrode. A 50W-halogen lamp varying with 5500, 11000, 20000 Lx was irradiated from the backside of the silicon wafer. The temperature of the electrolyte was thermostatically at 288K. The etching rate increases with increasing the concentration of hydrofluoric acid from 0.5 to 2.0M and levels off. The presence of organic additive like ethanol and inorganic additive like ammonium chloride accelerates the etching rate. Comparing the anodic potentiodynamic polarization curves of n-type silicon wafer in 2.0M HF, 2.0M HF+8.0M EtOH, and 2.0M HF+16.0M EtOH electrolytes, regardless in the dark or under illumination, one obtains that the corrosion current density and passive current density for the silicon are the highest in the presence of 16.0 M EtOH, and they decrease with decreasing the concentration of ethanol. Certainly, both corrosion and passive current are much higher (roughly two orders of magnitude) under the illumination. Addition of ethanol and ammonium salt into the hydrofluoric acid also takes the advantage that the pores not only have similar depth but also with smooth surface. The mechanism of the photo-electrochemical reaction is discussed.

### 2:00 PM

**BB3, Effect of Substrate Resistivity on Formation of Porous SiC:** T. Das<sup>1</sup>; S. I. Soloviev<sup>1</sup>; J. Bai<sup>2</sup>; P. I. Gouma<sup>2</sup>; T. S. Sudarshan<sup>1</sup>; <sup>1</sup>University of South Carolina, Electl. Eng., 301 S. Main St., Columbia, SC 29208 USA; <sup>2</sup>State University of New York at Stony Brook, Dept. of Matls. Sci. & Eng. 314 Old Engineering Bldg., Stony Brook, NY 11794-2275 USA

Porous layers obtained by electrochemical anodization of silicon carbide in solutions of hydrofluoric acid find growing interest in wide bandgap semiconductor technology. Among many parameters which effect the pore morphology, (such as current density, voltage, time of anodization, composition of electrolyte, etc.) substrate resistivity plays a significant role. In this work, we investigated the surface and pore morphology of SiC with respect to the effect of varying substrate resistivity used during electrochemical anodization. Porous silicon carbide (por-SiC) samples were prepared using n-SiC wafers with resistivity varying from 0.01 to 0.50 W×cm purchased from CREE Research, Inc. and Bandgap Technologies. Photo-assisted electrochemical etching was performed on silicon-terminated faces of the samples using a 150 W mercury lamp and a mixture of HF (1): Ethanol (1) as electrolyte for a time period of 1-40 minutes. The applied current density was varied between 1 mA/cm<sup>2</sup> and 40 mA/cm<sup>2</sup>. Thicknesses of the porous layers were measured by the cylindrical groove technique. In order to study the porous structure beneath the surface, some samples were subjected to dry etching by RIE to remove a thin (0.1-0.3 µm) so-called skin layer. Pore morphology of the formed porous layers was analyzed by SEM and TEM techniques. It has been noticed that at the same conditions of anodization (current density, time, electrolyte solution) the pore propagation depth increases with the decrease of substrate resistivity, while the pore diameter increases with the increase in substrate resistivity. Possible mechanism of this phenomenon is discussed in this work.

### 2:20 PM Student

**BB4, A Comparison of Schottky Diode Performance on Porous and Conventional SiC Substrates:** *Ramya Chandrasekaran*<sup>1</sup>; Marina Mynbaeva<sup>2</sup>; Shailaja Rao<sup>1</sup>; Michael C. Smith<sup>1</sup>; C. Dalton<sup>3</sup>; Michael Jenkins<sup>3</sup>; Michael MacMillan<sup>3</sup>; Stephen E. Sadow<sup>1</sup>; <sup>1</sup>University of South Florida, Ctr. for Microelect. Rsrch., 4202 E. Fowler Ave., ENB 118, Tampa, FL 33620 USA; <sup>2</sup>Ioffe Institute, SiC Grp., SiC Dr., St. Petersburg 194021 Russia; <sup>3</sup>Sterling Semiconductor, SiC Grp., 3401 Cragmont Dr., Tampa, FL 33619 USA

The goal of this research was to compare devices fabricated on porous and non-porous silicon carbide. Silicon carbide (SiC) is an excellent

semiconductor for electronic devices capable of operation at high power levels and high temperatures, due to its wide band gap, high electric field breakdown, and superior thermal and chemical properties. Therefore devices based on SiC offer fast switching characteristics and high-power handling capability. Unfortunately, the poor substrate quality of commercial crystals results in epitaxial (device) layers that have a significant concentration of crystallographic and point defects, thus limiting the yield and performance of devices made on these wafers. One method being explored to improve the epi quality is to use a porous substrate. This has led to an intense interest in porous silicon carbide (PSC) recently, where evidence of improved materials properties has been observed. Of particular interest is the reduction in optically active recombination centers such as the LI PL line, which seems to indicate that epi layers grown on PSC have a reduced point defect character. The next step in this research is to compare the performance of devices on both conventional and PSC substrates. In this paper, we report preliminary results of such a study. Both lateral and vertical Schottky diodes were fabricated. This arrangement permits direct evaluation of device performance in both configurations and might indicate if PSC is suitable for vertical power devices. A two-dimensional device simulation tool, MEDICI, was used to optimize the basic structure and doping of the SiC schottky diode fabricated on standard SiC substrates. A preliminary study has already been performed whereby a difference in diode performance was observed. Through the MEDICI simulations, we optimized the epi-layer doping by comparing the breakdown voltages for different doping levels. Device fabrication was as follows: A wafer was prepared to be half porous (PSC) and half initial (STD) so that an epitaxial layer could be grown on both regions simultaneously. A 5mm thick n-type epitaxial layer was grown with a target doping density of  $5E15 \text{ cm}^{-3}$  (n-type). The PSC and STD Schottky diodes were then fabricated using a metal-lift-off process (Ni Schottky barriers were e-beam evaporated) and tested to compare the performance of both types of diodes. Ni was used as the backside ohmic contact. Experimental results comparing the breakdown voltage, forward voltage drop and ideality factor will be presented.

#### 2:40 PM Student

**BB5, Design, Fabrication and Characterization of Nanostructured Semiconductor SiC-Based Catalytic Material System:** G. Akshoy<sup>1</sup>; B. A. Grayson<sup>1</sup>; S. E. Saddow<sup>2</sup>; M. Mynbaeva<sup>3</sup>; J. T. Wolan<sup>1</sup>; <sup>1</sup>University of South Florida, Cheml. Eng. Dept. & Ctr. for Microelect. Rsrch., Tampa, FL 33620 USA; <sup>2</sup>University of South Florida, Electl. Eng. Dept. & Ctr. for Microelect. Rsrch., Tampa, FL 33620 USA; <sup>3</sup>Ioffe Institute, St. Petersburg 194021 Russia

We report on the relationships of the structure and composition of nanoporous crystalline SiC-based semiconductor/metal-oxide systems with their catalytic activity and selectivity in heterogeneous catalytic processes. Duplication of the chemical constitution of a good catalyst is no guarantee that the solid produced will have any catalytic activity. This observation suggests that it is the physical or crystalline structure that somehow imparts catalytic activity to a material. This view is strengthened by the fact that heating a catalyst above a certain critical temperature may cause it to lose its activity, often permanently. Catalytic activity is electronic in nature and not well understood. Nanoporous SiC systems are expected to be useful as active catalytic supports due to their high number of low-coordinated edge and corner sites, their high chemical and thermal stability, and the possibility for electrocatalysis reactions because of the semiconducting nature of the substrate. For low-temperature methane oxidation (a very strong green-house gas), results thus far have revealed a reduction in ignition temperature by almost 50% as compared to the uncatalyzed reaction as shown in the figure below. Elemental and chemical-state identification via photoelectron spectroscopy of the material are presented. Several structure sensitive techniques including X-ray diffraction (XRD) in  $\bar{u}$ -2 as well as scanning electron microscopy (SEM) to examine crystal structure and surface morphology are included.

#### 3:00 PM

**BB6, Ferromagnetism in Mn Doped Porous GaN-From Clusters to Crystals:** G. P. Das<sup>1</sup>; B. K. Rao<sup>1</sup>; P. Jena<sup>1</sup>; <sup>1</sup>Virginia Commonwealth University, Physics Dept., Richmond, VA 23284-2000 USA

Porous GaN is characterized by internal surfaces whose morphology depends on the pore size. The binding of Mn atoms to these pores and their magnetic coupling will not only depend on the atomic structure of the internal surfaces, but also on the distance that separates the two

transition metal atoms. Factors that govern the magnetic coupling depend on the site Mn atoms bind to and the strength of its magnetic moment. To understand these factors, first-principles calculations based on density functional theory with generalized gradient approximation for exchange and correlation have been carried out by doping Mn atoms into GaN clusters as well as crystalline form. These two very different forms of matter exhibit different atomic arrangement and coordination numbers. The calculations reveal that the magnetic moments localized at the Mn sites couple ferro-magnetically irrespective of whether they are doped to clusters or crystalline form of GaN. We have used molecular orbital theory and the conjugated gradient method for optimizing the geometries of  $(\text{GaN})_x\text{Mn}_2$  ( $x < 4$ ) clusters. The electronic band structure and the magnetic properties of Mn doped GaN were calculated using a 32 atom super cell within the tight binding linearized muffin tin orbital (TB-LMTO) method. In small clusters, all the atoms of GaN are on the surface while in crystal they constitute bulk atoms. As cluster size increases, the geometry of  $(\text{GaN})_x$  clusters change as do the coordination numbers. We find the binding of Mn atoms to GaN clusters as well as their clustering to be energetically favorable. Since the atomic morphology of porous GaN is expected to be intermediate between that of clusters and crystal, the above results suggest that not only Mn atoms can be incorporated into porous GaN, but their coupling would remain ferro-magnetic. A magnetic moment of about  $4\mu_B/\text{Mn}$  atom is expected.

## Session CC: Nitride Device Processing: Contacts, Etching, and Dielectrics

Friday AM

Room: Lotte Lehmann

June 28, 2002

Location: University of California

*Session Chair:* Suzanne Mohny, Pennsylvania State University, Dept. of Matls. Sci. & Eng., 109 Steidle Bldg., University Park, PA 16802 USA

#### 8:20 AM Student

**CC1, Thermal Stability of Ti/Al/Mo/Au Ohmic Contacts on N-GaN:** Deepak Selvanathan<sup>1</sup>; Vipan Kumar<sup>1</sup>; Ilesanmi Adesida<sup>1</sup>; <sup>1</sup>University of Illinois at Urbana-Champaign, Electl. & Compu. Eng., 319 Micro & Nanotech. Lab., Urbana, IL 61801 USA

The III-V nitride wide-band-gap direct semiconductors have been used to fabricate blue LEDs, laser diodes and high-power electronic devices. Recent developments in the crystal quality have enhanced the importance of the GaN devices for optoelectronic as well as high-temperature electronic applications. Besides good quality material, device technology requires low resistive, thermally stable ohmic contacts to achieve high performance GaN-based devices. Earlier Ti/Al metallization was used as ohmic contact. But at high temperatures, Al has the tendency to ball up resulting in a rough surface morphology. Also, the contact resistance degrades due to the formation of a thin insulating aluminum oxide on the surface of the contact. To avoid the propensity of oxidation at elevated temperatures, Ni/Au, Ti/Au, Pt/Au, Pd/Au have been added on top of the Ti/Al contact. Since Mo has a higher melting point compared to Ni, Ti, Pt and Pd, it is expected to act as a superior barrier between Al and Au. Therefore, it will be of great interest to investigate Ti/Al/Mo/Au as ohmic contact to n-GaN. In this paper, we present the performance of this novel ohmic contact metallization (Ti/Al/Mo/Au) on n-GaN layer. The results in terms of contact resistance and thermal stability for the Ti/Al/Mo/Au system are presented. This ohmic metallization exhibits good edge definition, which is highly desirable for the fabrication of high-performance high electron mobility transistors with high yield. In the present study we have varied the thickness of Mo from 250Å to 750Å and TLM measurements indicate that the optimum annealing temperature and time are 850°C and 30 seconds, respectively and the contact resistance as low as 0.13 ohm-mm has been achieved as shown in the figure. There has been no appreciable effect of the thickness of Mo on the ohmic contact resistance. These contacts are thermally stable up to 650°C for an annealing time of 25 hours with no observable degradation in contact resistance. Surface profilometry results show that



the surface roughness of the as-deposited contact is 2nm and that of the annealed ohmic contact is about 20nm, which is lower than the previously reported values for the Ti/Al/Ni/Au ohmic contacts. The results on the study of thermal stability of these contacts at higher temperatures will be presented. Ohmic contact formation mechanisms for the n-GaN layer will also be discussed.

#### 8:40 AM Student

**CC2, Improvement of Ohmic Contact on AlGaIn/GaN HEMT Using Inductively Coupled Plasma Etching:** *Derrick Hoy*<sup>1</sup>; Eng Fong Chor<sup>1</sup>; Tow Chong Chong<sup>1</sup>; <sup>1</sup>National University of Singapore, ECE, 10 Kent Ridge Crescent, Singapore 119260

Several contact metallization schemes on AlGaIn/GaN HEMTs have been reported. The conventional method is to deposit metal layers on the AlGaIn surface followed by annealing at high temperatures (850°C-950°C) to allow diffusion of the metal layers to the 2°. It has been found that even with such high annealing temperatures, an unreacted layer of AlGaIn remains, which acts a barrier against carrier tunneling hence increases the contact resistance. Metal contact on AlGaIn/GaN with Si implantation through an AlN cap layer was also reported. The AlGaIn region adjoining the metal contact became heavily doped to enhance carrier tunneling. A third method to facilitate ohmic contact formation was by means of n+ GaN re-growth on the source and drain regions. Prior to re-growth, RIE was used to etch the AlGaIn/GaN HEMT structure to a depth below the 2°. The added re-growth process means a higher production cost and may lead to a lower yield. In the present work, we explore a simpler way of forming ohmic contact on AlGaIn/GaN HEMT. ICP was used to etch away a thin layer of the HEMT structure prior to the metallization to the source and drain regions. Figure 1 shows the three ranges of etch depth investigated: (1) a few nanometers from the surface, (2) within the AlGaIn layer, and (3) below the 2°. The metallization scheme used was Ti/Al/Pd/Au and the contact properties were studied using LTM. Figure 2 shows the effect of etch depth on the contact resistance. The samples shown have been given an annealing at 650°C for 60s in N<sub>2</sub> ambient. No ohmic behavior was observed without annealing or using a lower annealing temperature of 550°C or 600°C. This implies that interfacial phase change during annealing is crucial to the formation of good ohmic contact. It is worth noting that our annealing temperature of 650°C is much lower compared to 850°C-950°C used in the conventional metallization scheme. An optimum etch depth exists and it is 9nm from the AlGaIn/GaN interface. The minimum specific contact resistance attained is about 3.18 x 10<sup>-7</sup> Ohm-cm<sup>2</sup>, which is approximately one-eighth the best value achieved by earlier reported metallization schemes. It is also observed in Figure 2 that etching pass the 2°, an etch depth used in the n+ re-growth method, can lead to a much higher contact resistance. This is probably due to current crowding at the metal/2° sheet charge contact region. In summary, the contact resistance is shown to depend on both the etch depth of the AlGaIn/GaN HEMT structure and the interfacial phase change during annealing. This may suggest a tunneling effect at the metal-semiconductor interface as being a crucial mechanism in ohmic behaviour on III-nitrides.

#### 9:00 AM Student

**CC3, Vanadium-Based Contacts to N-AlGaIn and N-AlGaIn/GaN Heterostructures:** *P. K. Wang*<sup>1</sup>; T. G. Pribicko<sup>1</sup>; K. O. Schweitz<sup>1</sup>; E. D. Readinger<sup>1</sup>; David Gotthold<sup>2</sup>; Milan Pophristic<sup>2</sup>; J. M. Redwing<sup>1</sup>; S. E. Mohney<sup>1</sup>; <sup>1</sup>Pennsylvania State University, Dept. of Matls. Sci. & Eng., 207B Steidle Bldg., University Park, PA 16802 USA; <sup>2</sup>Emcore Corporation, Elect. Matls., 394 Elizabeth Ave., Somerset, NJ 08873 USA

Most ohmic contacts to n-AlGaIn/GaN heterostructures employ a Ti layer deposited directly on the semiconductor followed by an Al layer. Additional layers such as Pt/Au, Ti/Au, or Ni/Au are frequently added next. These contacts yield low resistances but typically require annealing temperature above 800°C. In an attempt to identify low resistance ohmic contacts requiring only moderate annealing temperatures on n-AlGaIn/GaN heterostructures and alternative contacts for n-AlGaIn of high Al fraction, V-based contacts were selected for study because of the stability of the low work function VN and its potential for forming a low resistance ohmic contact. V/Al/Pt/Au contacts of varying layer thicknesses were fabricated on n-Al<sub>0.3</sub>Ga<sub>0.7</sub>N/GaN heterostructures. The V (15 nm)/Al (85 nm)/Pt (50 nm)/Au (50 nm) contacts yielded the lowest resistance with a specific contact resistance of 1 x 10<sup>-5</sup> Ohm-cm<sup>2</sup> after annealing at 650°C for 30 s in N<sub>2</sub>. All Ti/Al/Pt/Au contacts in this study yielded specific contact resistances higher than 10<sup>-3</sup> Ohm-cm<sup>2</sup> after annealing at this condition. Specific contact resistances lower than 10<sup>-5</sup> Ohm-cm<sup>2</sup> were

found with optimized Ti/Al/Pt/Au contacts, but annealing at 850°C or higher was required. The role of the Al, Pt, and Au layers were next studied by omitting each layer in turn from the V/Al/Pt/Au contact and annealing at temperatures up to 750°C. Omitting the Al layer resulted in a rectifying contact, revealing that Al is necessary for ohmic contact formation. Without the Au layer, the contact was found to become ohmic only after annealing at higher temperatures and to exhibit a significantly higher minimum contact resistance. On the other hand, a V/Al/Au contact was found to yield specific contact resistances similar to those of the optimum V/Al/Pt/Au contact, indicating that the Pt layer does not play an important role in the formation of this low-resistance ohmic contact. Materials characterization of the contacts is now underway to further clarify the role of the layers. As the Al fraction in AlGaIn increases, it becomes increasingly difficult to fabricate low resistance ohmic contacts to n-AlGaIn. Both V/Al/Pt/Au and Ti/Al/Pt/Au contacts were also studied on n-Al<sub>0.44</sub>Ga<sub>0.56</sub>N. In this case, the V/Al/Pt/Au contact yielded a lower specific contact resistance than did the Ti-based contacts we have tested so far for all annealing temperatures in the study (up to 900°C). The lowest specific contact resistance obtained for the optimum V-based contact was 7 x 10<sup>-5</sup> Ohm-cm<sup>2</sup> after annealing at 700°C for 30 s in N<sub>2</sub>. Further study on even more Al-rich n-AlGaIn layers is planned.

#### 9:20 AM Student

**CC4, Electric Properties of Ti/Al Ohmic Contacts to Sulfide-Passivated N-GaN:** *June-O Song*<sup>1</sup>; Seong-Ju Park<sup>1</sup>; Tae-Yeon Seong<sup>1</sup>; <sup>1</sup>Kwangju Institute of Science & Technology, Matls. Sci. & Eng., 1 Oryong-dong, Kwangju 500-712 S Korea

Formation of low resistance and thermally stable ohmic contacts to GaN is of great technological importance for short-wavelength optical and electronic devices. In order to improve the electrical properties of ohmic contacts and hence to enhance the optical and electrical performance of GaN-based devices, various surface treatments using KOH, HNO<sub>3</sub>/HCl, buffered oxide etch (BOE), (NH<sub>4</sub>)<sub>2</sub>S<sub>x</sub>, and Na<sub>2</sub>S solutions have been introduced. It was shown that the surface treatments with alcohol-based (NH<sub>4</sub>)<sub>2</sub>S<sub>x</sub> solutions results in an improvement of the ohmic contact property. It is, however, known that surface treatments with some of sulfur-containing solutions, e.g., (NH<sub>4</sub>)<sub>2</sub>S<sub>x</sub>, may leave the partial Ga and As oxides on the GaAs surface and the sulfur passivation is unstable in ambient air. For this reason, thioacetamide CH<sub>3</sub>CSNH<sub>2</sub> solution was used to modify GaAs surfaces and was found to be very effective for the removal of the surface oxide and the formation of the sulfur passivation layer on the GaAs surface. Surface treatments with CH<sub>3</sub>CSNH<sub>2</sub> have not been hitherto performed on GaN systems. In addition, no detailed annealing study of sulfide-treated contacts has been reported. In this work, we investigate the passivation effects of CH<sub>3</sub>CSNH<sub>2</sub>/NH<sub>4</sub>OH solution on Ti (30 nm)/Al (80 nm) ohmic contacts to n-GaN:Si (n<sub>d</sub> = 3x10<sup>18</sup> cm<sup>-3</sup>) and the annealing treatment dependence of the electrical properties of the samples. It is shown that the sulfide treatment results in a drastic increase in the photoluminescence intensity, compared with that of the untreated sample. Current-voltage (I-V) measurements show that the sulfide treatment significantly improves specific contact resistance (which was measured using the TLM method). For example, the untreated sample produces 2.4x10<sup>-2</sup> Ohm-cm<sup>2</sup>, while the sulfide-treated as-deposited sample yields 4.8x10<sup>-4</sup> Ohm-cm<sup>2</sup>. It is also shown that annealing of the sulfide-treated sample (at 700°C) results in a specific contact resistance of 3.1x10<sup>-6</sup> Ohm-cm<sup>2</sup>. X-ray photoemission spectroscopy (XPS) results show that the Ga 2p core levels shift toward the higher binding energy-side by 0.2 eV for the sulfide-treated sample and by 0.4 eV for the annealed (sulfide-treated) sample, compared with that of the untreated one. It is further shown that the intensity of O 1s core level largely decreases with the sulfide treatment. Based on the I-V and XPS results, the sulfide and annealing treatment dependence of the specific contact resistance is discussed in terms of the combination of the effective removal of oxide on the GaN surface and the shift of the surface Fermi level toward the conduction band edge.

#### 9:40 AM Student

**CC5, Thermally Stable Capping Technology for Ti/Al Ohmic Contacts to N-GaN:** *Christopher M. Peltol*<sup>1</sup>; Y. A. Chang<sup>2</sup>; Yong Chen<sup>3</sup>; R. S. Williams<sup>3</sup>; <sup>1</sup>University of Wisconsin-Madison, Matls. Sci. Prog., 1509 University Ave., Madison, WI 53706 USA; <sup>2</sup>University of Wisconsin-Madison, Matls. Sci. & Eng., Madison, WI 53706 USA; <sup>3</sup>Hewlett-Packard Laboratories, Quantum Sci. Rsrch., 3500 Deer Creek Rd., Palo Alto, CA 94304 USA

We have developed a TiAl<sub>3</sub> cap for Ti/Al ohmic contacts to n-GaN that improves upon the shortcomings of many currently available capping technologies. Since the most successful ohmic contacts to n-GaN almost always contain the Ti/Al multilayer structure, special steps must be taken to provide oxidation resistance so the full potential of this contact can be achieved and implemented in a device. The current caps, though, are plagued with undesirable qualities for ohmic contacts in this system. Our contact structure in the present study is TiAl<sub>3</sub> (50 nm)/Al (115 nm)/Ti (30 nm), where the Ti layer is the bottommost layer in contact with the n-GaN substrate. We deposited the TiAl<sub>3</sub> film by sputtering from a compound target of the proper composition, whereas the elemental layers were sputter deposited from elemental targets. We have found that the TiAl<sub>3</sub> cap allows us to achieve a best specific contact resistance ( $\bar{n}_c$ ) of 1.66E-5  $\Omega$  cm<sup>2</sup> following a 10 min anneal at 600°C in an oxygen-controlled UHP Ar ambient. This is an improvement of a factor of 2 over the best of our previous uncapped Ti/Al contacts on the same substrate. We also fabricated a Au (80 nm)/Ni (20 nm)/Al (80 nm)/Ti (25 nm) contact on the same substrate, and we measured a  $\bar{n}_c$  of 1.84E-5  $\Omega$  cm<sup>2</sup> following a 15 s anneal at 900°C in an oxygen-controlled UHP Ar ambient. A TiAl<sub>3</sub>-capped contact was also annealed for up to 20 min at 600°C in air and compared with a Au/Ni/Al/Ti contact annealed under the same conditions. The TiAl<sub>3</sub>-capped contact did not experience any performance degradation at all and was found to have a  $\bar{n}_c$  of 1.10E-5  $\Omega$  cm<sup>2</sup> while the Au/Ni/Al/Ti contact was found to be significantly worse with a  $\bar{n}_c$  of only 1.4E-4  $\Omega$  cm<sup>2</sup>. TiAl<sub>3</sub> provides particularly good oxidation resistance because it forms a thin aluminum oxide at the surface which prevents further oxidation of the rest of the contact. Additionally, the TiAl<sub>3</sub> is in thermal equilibrium with the Al layer, thus full reaction between the Ti and Al layers is possible without introducing other elements into the reaction that can possibly migrate to the metal/semiconductor interface. Auger depth profiling was performed to characterize the redistribution of the layers in the contact structure following the thermal treatment. TiAl<sub>3</sub>-capped Ti/Al contacts are particularly attractive for use in device systems that can benefit from oxidizing anneals to improve ohmic contact to p-GaN, such as laser diodes.

#### 10:00 AM Break

#### 10:20 AM Student

**CC6, Electrical Properties of Metal Contacts on KRF Eximer Laser Irradiated GaN:** *Jong Kyu Kim*<sup>1</sup>; Ho Won Jang<sup>1</sup>; Jeremy Schroeder<sup>2</sup>; Eric Caletton<sup>2</sup>; Timothy Sands<sup>2</sup>; Myung Cheol Yoo<sup>3</sup>; Jong-Lam Lee<sup>1</sup>; <sup>1</sup>Pohang University of Science and Technology (POSTECH), Matls. Sci. & Eng., San 31, Hyoja-Dong, Nam-Gu, Pohang, Kyungbuk 790-784 S. Korea; <sup>2</sup>University of California–Berkeley, Matls. Sci. & Eng., 577 Evans Hall, Berkeley, CA 94720-1760 USA; <sup>3</sup>Oriol, Inc., R&D, 3390 Viso Ct., Santa Clara, CA 95054 USA

Laser irradiation method have been recently introduced to GaN device technology not only for the activation of p-GaN film, but also for “laser lift-off” to separate GaN from sapphire substrate and transfer the GaN film onto Si or GaAs substrate. Although the laser irradiation could largely affect the surface and the bulk of the GaN, and hence the electrical properties of the metal contact on the GaN, only a few works have been conducted on the laser-induced changes in GaN. In the present work, we studied effects of laser irradiation to undoped GaN on electrical properties of metal contacts on GaN. The GaN films used in this study were grown on c-plane sapphire by metalorganic chemical vapor deposition technique. An undoped GaN layer with a thickness of 1  $\mu$ m was grown on the sapphire substrate at 550°C, followed by a 1  $\mu$ m-thick undoped GaN layer at 1050°C. The electron concentration of films was measured to be 5.4x10<sup>16</sup> cm<sup>-3</sup> by Hall measurement. The samples were irradiated in air with KrF pulsed eximer laser (30 ns pulse width, 200 mJ/cm<sup>2</sup>). The laser-induced changes in chemical bonding states were examined using synchrotron radiation photoemission spectroscopy (SRPES). Schottky diodes were fabricated on both the laser-irradiated and the as-grown GaN. Pt (100 nm) Schottky contact and Ti/Al (40/120 nm) ohmic contact were deposited in sequence using an e-beam evaporator. The C-V characteristic of the Schottky diode was measured. From the plot of 1/C<sup>2</sup> as a function of applied voltage, the built-in potential for the laser-treated sample and the as-grown sample are calculated to be 1.02 and 0.83 eV, respectively. By substituting the permittivity of GaN (0.95  $\epsilon_0$ , where  $\epsilon_0$  is the permittivity in vacuum) and the area of the Pt Schottky diode (7.85x10<sup>-9</sup> m<sup>2</sup>) to the plot of 1/C<sup>2</sup>-V, the electron concentration in the as-grown sample was determined to be 4.6x10<sup>16</sup> cm<sup>-3</sup>, which agrees

with the value measured from Hall measurement. It was found that the electron concentration increased to 1.1x10<sup>17</sup> cm<sup>-3</sup> after the laser treatment. In addition, the surface state density increased from 5.2x10<sup>11</sup> to 6.8x10<sup>11</sup>cm<sup>-2</sup> after the laser treatment. SRPES results shows that the Ga 3d and the N 1s core levels shifted to a lower binding energy and the relative Ga-to-N ratio increases from 1 to 1.8 after the laser treatment. This indicates that laser treatment induced a number of N vacancies, acting as donors for electrons, leading to the increase of the surface state density and the carrier concentration. Moreover, the intensity of Ga-O bond increases indicating that Ga-related oxides produced during the laser treatment, leading to the increase of the Schottky barrier height.

#### 10:40 AM

**CC7, Transparent Multilayered Schottky Contacts to GaN for Metal-Semiconductor-Metal Photodetectors:** *Dong S. Wu*<sup>1</sup>; Ray H. Horng<sup>2</sup>; Shun C. Hsu<sup>2</sup>; Wen H. Lan<sup>3</sup>; <sup>1</sup>National Chung Hsing University, Dept. of Matls. Eng., 250 Kuo Kuang Rd., Taichung 402 Taiwan; <sup>2</sup>National Chung Hsing University, Inst. of Precision Eng., 250 Kuo Kuang Rd., Taichung 402 Taiwan; <sup>3</sup>Chung-Shan Institute of Science and Technology, Matls. R&D Ctr., Box 90008-8-10, Lun-Tang, Tao-Yuan 324 Taiwan

The current interest in developing ultraviolet photodetectors (PDs) is driven by applications in military counter measures, engine monitoring, flame detection and solar UV detection. The metal-semiconductor-metal (MSM) device consists of a photoabsorbing semiconductor layer on which a pair of interdigitated Schottky contacts is deposited. However, the responsivity of the MSM PDs is low due to the blocking of incoming light by the metal electrodes. Although this problem can be solved by backside illumination, it will also create critical problems in optical lithography alignment, device processing, and chip packaging. Therefore, it is very attractive to use a transparent conductor, such as indium tin oxide (ITO), for the contact electrode of MSM PDs. In this work, the transparent ITO/GaN Schottky contacts have been fabricated by the insertion of various intermediate layers (Ti, TiO<sub>2</sub>, and TiO<sub>2</sub>/Ti). Particularly, the thin TiO<sub>2</sub>/Ti interlayer at the ITO-GaN interface was found to result in a significant decrease in the dark current, and an increase in peak transmittance for the first time. All the undoped GaN samples used in this study were epitaxially grown on c-face sapphire substrates by metalorganic chemical vapor deposition. The carrier concentration was about 1x10<sup>17</sup> cm<sup>-3</sup>. Conventionally, a thin Ti layer was used to assist in the adhesion of ITO on GaN. However, the leakage current of the ITO/Ti/GaN Schottky contact was still high due to the formation of TiN at the Ti/GaN interface. Since the Ti atoms react with the GaN, a high concentration of nitrogen vacancies is created near the interface. This makes the GaN surface heavily doped, yielding the degraded Schottky performance. Figs. 1(a) and (b) compare the dark current-voltage characteristics of ITO/GaN back-to-back Schottky contacts with Ti and TiO<sub>2</sub> interlayer, respectively. It is found that the dark current of the ITO/TiO<sub>2</sub>/GaN contact is nearly three orders of magnitude lower than that of the ITO/Ti/GaN contact. Despite low dark current can be achieved in the ITO/TiO<sub>2</sub>/GaN structure, the responsivity decreases due to the TiO<sub>2</sub> barrier. The problem can be solved by the insertion of a thin TiO<sub>2</sub>/Ti interlayer at the ITO/GaN interface. To verify this ideal, an MSM structure was fabricated on the 1.5-mm-thick GaN epilayer using an interdigitated electrode mask set. The electrode fingers were designed to be 2-mm wide and 100-mm long with a 2-mm-wide spacing. The total detector area is 100x78 mm<sup>2</sup>. Table 1 summarizes the data on responsivity, UV/visible contrast, transmittance, and dark current. It is found that the peak transmittance increases from 77% to 80% and the responsivity increases from 2.0 A/W to 2.4 A/W for the ITO/GaN MSM PDs with a TiO<sub>2</sub>/Ti interlayer. Details of the thickness effect of these multilayer stacks and related mechanism will be discussed.

#### 11:00 AM

**CC8, High-Temperature NH<sub>3</sub> and Low-Temperature Plasma-Assisted N-Atom Surface Cleaning of GaN Prior to GaN-Dielectric Interface Formation for Passivation and Active Layer Formation in Advanced Device Structures:** *C. Bae*<sup>1</sup>; T. E. Cook, Jr.<sup>1</sup>; R. J. Nemanich<sup>1</sup>; G. Lucovsky<sup>1</sup>; <sup>1</sup>North Carolina State University, Dept. of Physics, Raleigh, NC 27695 USA

GaN has emerged as important material for opto-electronic and high temperature/high power device applications. As such, surface cleaning prior to surface passivation has become an important issue in device processing. This paper compares two different approaches to surface cleaning and passivation: i) a high-temperature, 860°C process in which the GaN surface is exposed to NH<sub>3</sub>, and ii) a low-temperature, 300°C process in which the GaN surface is exposed to N-atoms/ions extracted

from a remote N<sub>2</sub>/He plasma, each followed by a different process for dielectric interface formation. The effectiveness of these cleaning processes has been monitored by on-line AES. After the cleaning processes, there is no detectable C or Cl (from an ex-situ HCl surface etch), and only a very small residual O-atom signal. Following the high-temperature NH<sub>3</sub> cleaning process, the GaN dielectric interface, and a SiO<sub>2</sub> dielectric layer are formed by plasma-assisted oxidation of a sacrificial Si layers, in which thin layers of Si, increasing from 0.2nm to 0.9nm are sequentially deposited and then plasma oxidized. The GaN-dielectric interface is formed during the plasma-assisted oxidation of the first few sacrificial Si layers. Changes in the Ga 3p<sub>3/2</sub>, Si 2p, O1s, Ga 3d and N1s core levels are monitored by on-line XPS, and track the evolution of the interface, which includes Ga-O bond formation, and development of the SiO<sub>2</sub> dielectric layer. Following the low-temperature plasma-assisted N ion cleaning process, the interface and dielectric layer are formed by a two-step process that provides separate and independent control of the interface, an ultra-thin Ga<sub>2</sub>O<sub>3</sub> interfacial oxide and the SiO<sub>2</sub> dielectric. The first step is plasma-assisted oxidation process using either O<sub>2</sub>/He or N<sub>2</sub>O/He source gases that forms the interface and the ultra-thin Ga<sub>2</sub>O<sub>3</sub> layer. This process is self-limiting with power law kinetics that are similar to those for the plasma-assisted oxidation of Si. The kinetics have been determined from analysis of on-line AES features associated with Ga, N and O. The quality of the interfaces formed by the high-temperature NH<sub>3</sub> process has been studied by on-line XPS and UPS, and levels of fixed charge, and interface traps have been estimated from interfacial band-bending. This approach also yields a determination of interfacial band offset energies between the GaN valence and conduction bands, and the corresponding bands of the SiO<sub>2</sub> dielectric. The quality of the interface and dielectric layer for the two-step plasma processing has been evaluated by the fabrication of test devices, MOS capacitors, as well as normally-on FETs. The paper will present direct comparisons of these two approaches to GaN cleaning and interface formation based on photoluminescence spectroscopy, and on the evaluation of MOS devices.

#### 11:20 AM

**CC9, Growth and Characterization of Magnesium Oxide Gate Dielectrics on Gallium Nitride:** Brent Gila<sup>1</sup>; Jihyun Kim<sup>2</sup>; Andrea Onstine<sup>1</sup>; Kerry Siebein<sup>1</sup>; Cammy Abernathy<sup>1</sup>; Fan Ren<sup>2</sup>; Steve Pearson<sup>1</sup>; <sup>1</sup>University of Florida, Matls. Sci. & Eng., PO Box 116400, Gainesville, FL 32611 USA; <sup>2</sup>University of Florida, Cheml. Eng., PO Box 116005, Gainesville, FL 32611 USA

GaN field effect transistors (FETs) have attracted considerable research interest due to their potential use in high temperature and high power electronics. GaN metal oxide semiconductor FETs (MOSFETs) are expected to provide superior performance to GaN metal semiconductor FETs (MESFETs) due to reduced gate leakage. Further, GaN MOSFETs offer the possibility of fabricating enhancement mode rather than depletion mode devices. Fabrication of high performance metal oxide semiconductor field effect transistors (MOSFETs) on gallium nitride will require good interfacial electrical characteristics, good thermal and chemical stability, and process ability. Devices with gate dielectrics of AlN, Ga<sub>2</sub>O<sub>3</sub>(Gd<sub>2</sub>O<sub>3</sub>), Gd<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, and Si<sub>3</sub>N<sub>4</sub> have all been previously reported<sup>1-5</sup>. While dielectrics such as SiO<sub>2</sub> and Ga<sub>2</sub>O<sub>3</sub>(Gd<sub>2</sub>O<sub>3</sub>) have demonstrated low to moderate interface state densities, questions remain about their thermal stability and reliability, particularly for use in high power or high temperature wide bandgap devices. All oxide growth was carried out in a Riber 2300 MBE using MOCVD grown n-GaN/sapphire substrates. Preparation of the as-received n-GaN substrates consisted of a wet chemical etch, followed by a UV-ozone exposure and a final wet etch. This was followed by a thermal anneal at 650°C in the MBE growth chamber to create a streaky (1x3) RHEED pattern<sup>6</sup>. The magnesium oxide was grown from magnesium (5N) in a standard effusion oven and atomic oxygen from an RF (13.54MHz) plasma source. Substrate temperature was 100°C and film thickness was 100nm. RHEED patterns taken from the surface during growth indicate a gradual transition from single crystal to poly-crystal. This was also confirmed from cross-section TEM images which show that the MgO is single crystal at the interface and then upon reaching a thickness of approximately 3.6nm, becomes polycrystalline. Diodes were fabricated from these materials to test the electrical properties of the dielectric and the dielectric/GaN interface. A forward breakdown field of 2.3 MV/cm was measured at 5.1 mA/cm<sup>2</sup>. A corresponding interface state density of 4x10<sup>11</sup> cm<sup>-2</sup>eV<sup>-1</sup> was calculated for the diode using the AC conductance method. The sample was stored

at room temperature and humidity for 15 weeks and retested. There was no difference measured in the IV or the CV. This indicates that the MgO under the gate does not degrade in air at room temperature. <sup>1</sup>S. Arulkumar et. al., Appl. Phys. Lett. 73, 809 (1998); <sup>2</sup>B. Gaffey et. al., ECS Proceedings, 99-4, 174 (1999); <sup>3</sup>J. W. Johnson et al., J. Electrochem. Soc. 148, G303 (2001); <sup>4</sup>F. Ren et. Al., Solid State Ele. 42, 2177 (1998); <sup>5</sup>F. Ren et. al., Appl. Phys. Lett. 73, 3893 (1998); <sup>6</sup>B. P. Gila et al., Proceedings Volume 2001-1, p. 71, The Electrochemical Society Series(2001).

#### 11:40 AM Student

**CC10, Smooth, Selective Undercut of (In)GaN Achieved by Photoelectrochemical Wet Etching:** Yan Gao<sup>1</sup>; Andreas R. Stonas<sup>2</sup>; Ilan Ben-Yaacov<sup>2</sup>; Umesh Mishra<sup>2</sup>; Steven P. Denbaars<sup>1</sup>; Evelyn L. Hu<sup>2</sup>; <sup>1</sup>University of California–Santa Barbara, Matls. Dept., Santa Barbara, CA 93106 USA; <sup>2</sup>University of California–Santa Barbara, Electl. & Compu. Eng. Dept., Santa Barbara, CA 93106 USA

By now, there has been a variety of demonstrations of the utility of photoelectrochemical (PEC) wet etching for the effective and low-damage fabrication of GaN-based devices. PEC etching has also demonstrated rapid lateral etch rates: with illumination of the GaN through the sapphire substrate (so-called 'backside illumination'): a lower bandgap InGaN sacrificial layer was selectively removed, resulting in a deeply undercut structure. Those initial etches were used to successfully lift-off GaN structures from their sapphire substrate; however, there was a residual etch-related roughness that could compromise some device behavior. The studies described were carried out using *front*-side illumination to produce substantial lateral etch rates. The optimization of the etch conditions utilized the Taguchi approach; we were ultimately able to form the smoothly undercut structures shown in Figures 1 and 2. The samples used in this study are GaN/In<sub>x</sub>Ga<sub>1-x</sub>N/GaN heterostructures (x~8%, 600Å thick In<sub>x</sub>Ga<sub>1-x</sub>N layer) grown by MOCVD on a sapphire substrate. Ti/Au/Pt is deposited as the metal contact to the substrate, and PEC etching is carried out by using a KOH-water solution, with illumination from a Xe lamp. In order to selectively etch the InGaN layer, we interposed a n-GaN/sapphire 'filter' between the lamp and the sample, thus blocking out the shorter wavelength components of the Xe lamp. We systematically varied the intensity of the Xe lamp, the bias applied to the substrate, and the concentration of the KOH in the solution. We believe that the results show great promise as a technique for forming smooth, controllable undercut etches, applicable to the fabrication of electrical or optical apertures.

## Session DD: Biological/Electronic Interfaces

Friday AM Room: MultiCultural Theatre  
June 28, 2002 Location: University of California

*Session Chairs:* Carol I.H. Ashby, Sandia National Laboratories, MS 1425, PO Box 5800, Albuquerque, NM 87185-1425 USA; Evelyn L. Hu, University of California–Santa Barbara, Elect. & Compu. Eng. Dept., Santa Barbara, CA 93106 USA

#### 8:20 AM

**DD1, Silicon and Metal Oxide Biotechnology: New Routes to Catalytic Nanofabrication of High-Performance Materials:** Daniel Morse<sup>1</sup>; <sup>1</sup>University of California, Biomo. Sci. & Eng., CA Nanosys. Inst., Santa Barbara, CA 93106 USA

Biological systems synthesize a diversity of silica structures with a precision of nanoarchitectural control that frequently exceeds the present capabilities of human engineering. In contrast to the conditions of industrial manufacture, these biological syntheses occur under mild physiological conditions of low temperatures and pressures and near-neutral pH. Analyses of the proteins, genes and molecular mechanisms governing the formation of these composites revealed an unanticipated mechanism of synthesis with potential industrial applicability. We found that the silica spicules made by a marine sponge each contain an occluded axial filament of protein composed of repeating assemblies of three similar subunits we named "silicateins." Analysis of the purified protein subunits and the cloned silicatein DNAs reveals that the silicateins are highly

homologous to a family of hydrolytic enzymes. As predicted by this finding, we discovered that the silicatein filaments catalyze and spatially direct polycondensation to form silica, phenyl- and methyl-silsesquioxane from the corresponding silicon alkoxides at neutral pH and low temperature. Catalytic activity also is exhibited by the silicatein subunits obtained by disaggregation of the protein filaments, and those produced from recombinant DNA templates cloned in bacteria. Genetic engineering, used to produce variants of the silicatein molecule with substitutions of specific amino acid sidechains, in conjunction with computer-assisted molecular modeling, allowed us to probe the determinants of catalytic activity and confirm the identification of the amino acid sidechains required for hydrolysis of the silicon alkoxides. Based on these findings, we then predictively synthesized biomimetic diblock copolypeptides incorporating the essential features found to be required for catalysis. As predicted, these self-assembling synthetics mimic the activities of the native silicateins, catalyzing the polymerization of silica at neutral pH, while simultaneously directing the 3-dimensional structure of the resulting silicon-based-polymer composite. In addition to working with siloxane precursors, we discovered that the silicateins also catalyze structurally directed polycondensation of titanium oxide from an appropriate precursor. We now are exploring paths to harness the structure-directing activity of the silicateins and their biomimetics to produce ordered polysiloxanes, metal oxides and hybrid materials with enhanced coherence and optoelectronic performance, and to write nanostructural features of silica on silicon chips in a biotechnological analog of CMOS technology.

#### 8:40 AM Student

**DD2, Investigation and Characterization of Biomolecular Interactions with Inorganic Materials and Surfaces:** *Erin E. Gooch*<sup>1</sup>; Angela M. Belcher<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Chem. & Biochem., A5300, Austin, TX 78712 USA

In nature, proteins are known to direct the building of exquisite organic-inorganic hybrid crystal structures to make materials of highly selective orientation, polymorphology and crystallographic uniformity on nanolength scales. The elaborate architecture and regularity of such structures has not yet been duplicated by inorganic synthesis or biomimetic approaches. Harnessing the enormous synthetic potential of these self-organizing, highly selective natural biomolecules has proven difficult, despite more than twenty years of efforts. Here, we present a combinatorial method that has led to a better understanding of the interactions of biomolecules with the inorganic substrates they so elegantly control. By using this combinatorial method, we have screened a library of peptides against a common natural biomineral, calcium carbonate (CaCO<sub>3</sub>). By using techniques such as peptide sequence pattern analysis and sequence homology, we have been able to characterize the selected sequences by the discovered substrate-specific patterns. Furthermore, we are investigating peptide binding by use of Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and molecular dynamics modeling. The extension of these techniques to electronically interesting oxides such as lithium niobate (LiNbO<sub>3</sub>), barium titanate (BaTiO<sub>3</sub>), and lead titanate (PbTiO<sub>3</sub>) has unveiled some interesting similarities to the results found with calcium carbonate. Understanding the specific interactions of these selected peptides will lead us to engineer synthetic peptide systems with the ability to recognize specific inorganic materials and even nucleate a desired phase of the material of interest.

#### 9:00 AM Student

**DD3, Peptide Integration with Conductive Polymers for Nerve Cell Guidance:** *Kiley P. Miller*<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Dept. of Chem. & Biochem. MC A5300, Austin, TX 78712 USA

We are currently exploring new methods of ligand-substrate interaction via peptide selection to help promote nerve regeneration through novel ligand complexes. Peptides have been selected that recognize the molecular structures of poly (lactic-co-glycolic acid) (PLGA) and poly (pyrrole) (PPy) using a combinatorial library-phage display system. These peptides are able to chemically modify the substrate surface allowing biomolecule or glial cell attachment. Current studies utilize invasive techniques such as auto-grafts for nerve axon regeneration. We are investigating new biological hybrid materials to act as substrates in nerve guidance channels for the regeneration of peripheral nerve axons. We are characterizing these surfaces using the following techniques: atomic force microscopy, scanning electron microscopy, surface plasmon resonance spectroscopy, and X-ray photoelectron spectroscopy.

#### 9:20 AM Student

**DD4, Assembly of Quantum Dots by Ribosomal Molecular Machines:** *Ioana Pavel*<sup>1</sup>; Karen S. Browning<sup>1</sup>; Angela M. Belcher<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Dept. of Chem. & Biochem., Austin, TX 78712 USA

We have developed a method for organizing quantum dots by linking them to chemically reactive amino acids side chains (e.g., lysine, glutamic acid, and cysteine) and then integrating these amino acids into a polypeptide nascent chain through in vitro translation of an mRNA template. The use of this system would not only provide a new tool for probing fundamental biological processes (e.g. translation) but also provide a genetic code for the supramolecular assembly of new bioinorganic heterostructures using ribosomes as natural molecular machines. We have successfully synthesized tRNA in vitro and charged them with their corresponding amino acids. Following the charging of the tRNA, the side chain of the amino acid is covalently linked to a quantum dot either directly or through a heterobifunctional linker, which may vary in length and/or chemical properties. The result is a novel quantum dot-conjugated or nanocrystal-tRNA. The successful attachment of quantum dots to aminoacyl-tRNA and the subsequent translation of nanocrystal-polypeptides from mRNA templates are performed in vitro in cell-free systems and are verified by mass spectroscopy, electrophoresis, and high resolution TEM.

#### 9:40 AM

**DD5, Late News**

#### 10:00 AM Break

#### 10:20 AM Student

**DD6, Peptide Recognition of Magnetic Materials:** *Brian D. Reiss*<sup>1</sup>; Daniel J. Solis<sup>1</sup>; Angela M. Belcher<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Chem., Austin, TX 78712 USA

Ultrafine magnetic nanoparticles have numerous applications in magnetic memory devices, biosensors, and nanoscale electronics. Currently such materials are prepared as colloidal sols, and while these preparations yield monodisperse, crystalline solids, the dispersions are often expensive to prepare and usually lack long-term stability, limiting their applications. For this reason alternative synthetic strategies are currently under investigation. Peptide mediated synthesis of magnetic nanoparticles is one such alternative since it has previously been used to successfully synthesize semiconducting nanoparticles and since it should provide a low temperature alternative to the traditional preps of magnetic nanoparticles. To accomplish this goal, two combinatorial phage libraries were exposed to the surfaces of nanoparticulate thin films of magnetic materials. These phage libraries contained phage which were functionalized with either a random 12 mer or 7 mer peptide attached to their P<sub>3</sub> coat proteins. To date, FePt, CoPt, and Co have been investigated, and peptides have been isolated and identified which selectively bind to each of these surfaces. The binding properties of these peptides have been investigated. These peptides will be used to manipulate the nucleation of magnetic nanoparticles with control over the size and crystallinity of the nanoparticles.

#### 10:40 AM Student

**DD7, Bacterial Nanosynthesizers: In Vivo Biosynthesis of Cadmium Sulfide Nanocrystals:** *Rozamond Y. Sweeney*<sup>1</sup>; Chuanbin Mao<sup>1</sup>; Jifa Qi<sup>1</sup>; George Georgiou<sup>1</sup>; Brent Iverson<sup>1</sup>; Angela M. Belcher<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Chem. & Biochem., 2600 Speedway, Austin, TX 78712 USA

In living cells, cadmium ions are known to react with any free thiol, causing oxidative stress. Glutathione and other related thiol-containing peptides with the amino acid structure, (Glu-Cys)-n-Gly, sequester Cd(II) and template the formation of inert cadmium sulfide nanocrystals in yeast. The formation of these nanocrystals constitutes the Cd(II) detoxification response. We report the biosynthesis of CdS nanocrystals in bacteria *E. coli* incubated with cadmium chloride and sodium sulfide. The nanocrystals are stabilized against accretion, and the cells can be lysed to yield discrete quantum dots. We used the techniques of transmission electron microscopy, single molecule spectroscopy, and confocal microscopy to analyze the quantum dots and determine their chemical composition, size distribution, and internal structure. The diffraction patterns of the nanocrystals are consistent with wurtzite CdS. The nanocrystals exhibit a luminescence peak centered at 430nm when excited at 354nm. Additionally, the formation of nanocrystals in the cells can be monitored by exciting the cells with a UV laser under a confocal

microscope. Future directions for this work include the synthesis of different II-VI semiconductor quantum dots and also composite nanocrystals. This work lays the foundation for the use of bacteria to quickly screen for nanocrystal nucleation using the techniques of cell surface display and fluorescence activated cell sorting.

#### 11:00 AM Student

**DD8, Peptide-Directed Recognition, Nucleation and Control of II-VI Semiconductor Nanomaterials:** *Christine E. Flynn*<sup>1</sup>; Chuanbin Mao<sup>1</sup>; Julie Williams<sup>1</sup>; Angela M. Belcher<sup>1</sup>; <sup>1</sup>The University of Texas, Chem. & Biochem., Welch Hall 4.202, Austin, TX 78712 USA

Control of crystal structure, phase, orientation and nanostructural regularity of inorganic materials is an ability uniquely seen in biological systems on the molecular scale. We are currently developing new methods to pattern useful non-biological electronic materials on the nanometer scale using the principles of natural biological molecular recognition. We have mimicked biological selection through the screening of genetically engineered viruses to find peptide recognition specific to interesting II-VI semiconductor nanomaterials, such as zinc sulfide, cadmium sulfide, lead sulfide, and zinc selenide. Potential technological applications using such materials are possible through highly specific synthetic control, thus allowing exploitation of unique optical, electrical and optoelectronic properties that may lead to a wide variety of practical devices. This peptide combinatorial approach utilizes the inherent self-organizing, highly selective properties of biologically derived molecules. We have selected peptides that can nucleate and control aspect ratio and particle diameter of these materials. In aqueous, room temperature syntheses, these peptides show control over crystallographic structure and orientation of nanoparticles and nanowires. In addition, synthetic peptides and further genetic engineering techniques are being utilized to further show controlled nanoparticle crystal growth and arrangement. Using this peptide-directed recognition, we are organizing organic/inorganic materials into heterostructured assemblies.

#### 11:20 AM

**DD9, Building Quantum Dots into Solids with Well-Defined Shapes by Chemical and Biological Routes:** *Chuanbin Mao*<sup>1</sup>; Jifa Qi<sup>1</sup>; Christine E. Flynn<sup>1</sup>; Andrew Hayhurst<sup>2</sup>; George Georgiou<sup>3</sup>; Brent Iverson<sup>1</sup>; Angela M. Belcher<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Dept. of Chem. & Biochem., Austin, TX 78712 USA; <sup>2</sup>The University of Texas, Dept. of Cheml. Eng., Austin, TX 78712 USA; <sup>3</sup>University of Texas at Austin, Dept. of Biomed. Eng., Austin, TX 78712 USA

II-VI semiconductor quantum dots (QDs) exhibit a wide range of electrical and optical properties that are tunable by tailoring the sizes and shapes of the nanocrystals. When QDs are built into close-packed ensembles (QD solids), collective physical phenomena such as the evolution of the localized electron state of an individual QD to a delocalized electronic state will develop as neighboring QDs interact with each other. The inter-dot interactions result in new physical properties. QD solids have the potential for novel electronic, optical and optoelectronic applications that combine both the collective physical properties of coupled QDs and the unique physical properties of individual QDs. Consequently, wide interest has been stimulated in the preparation of QD solids by different processes. However, the QD solids prepared by those processes do not contain QDs in close contact and it is difficult to achieve well-defined shapes of QD solids prepared by other methods. Moreover, other synthesis techniques rely on specific substrates/matrix, where the QD solids are not easily transferred. A new chemical and biological process has been developed to prepare QD solids. QDs in solution were built in situ into a variety of three dimensional QD solids with well-defined shapes: needles, disks, rods, spheres, bundles, stars, ribbons and transition structures (TSs). Design strategies utilizing a novel cold treatment (-25°C to 85°C) process provided control over these shapes independent of the II-VI materials used. The nanostructures (QD orientation, size, shape, arrangement) of the QD solids are controlled by the cold treatment process and a specific cold treatment mode produces QD solids with a particular shape and nanostructure. Transformation occurred between different shapes by the rearrangement of the QDs within the QD ensembles. Using the cold treatment strategy, genetically engineered bacteriophage are applied to build ZnS QDs into QD solid wires. Due to the specific interaction between ZnS and a peptide that was selected against ZnS by phage display and expressed on the phage, ZnS QDs are nucleated and aligned along the phage coat with control of crystal structures and crystallographic orientation. The QD-virus solid wires are iso-

lated or close packed, depending on the temperature used. The cold treatment strategy is versatile and has been applied to several II-VI QDs and may be extended to other QD systems and other chemical approaches. QDs in the solids are 3 to 5nm in size with inter-dot distance less than 4nm. Our QD solids can be easily transferred to Si substrates. Photoluminescence data on the QD solids shows electronic coupling between QDs inside a solid. The QD solids are expected to have novel electronic, optical and optoelectronic applications and can serve as new model systems for further research on collective physical phenomena of QD solids.

#### 11:40 AM

**DD10, Late News**

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## Session EE: Oxide Heteroepitaxy

Friday AM

Room: UCEN State Street

June 28, 2002

Location: University of California

*Session Chairs:* Ho Nyung N. Lee, Max-Planck-Institute of Microstructure Physics, Exp. Dept. II, Weinberg 2, Halle/Saale 06120 Germany; V. Nagarajan, University of Maryland, Matls. & Nuclear Eng., Rm. 1108, College Park, MD 20742 USA

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#### 8:20 AM

**EE1, Extended Defects and Misfit Accommodation in Epitaxial Ba<sub>0.3</sub>Sr<sub>0.7</sub>TiO<sub>3</sub> Thin Films Grown on (001) LaAlO<sub>3</sub>:** *C. J. Lu*<sup>1</sup>; L. A. Bendersky<sup>1</sup>; K. S. Chang<sup>2</sup>; I. Takeuchi<sup>2</sup>; <sup>1</sup>National Institute of Standards and Technology, Metall. Div., 100 Bureau Dr., MS 8554, Gaithersburg, MD 20899 USA; <sup>2</sup>University of Maryland, Dept. of Matls. Sci. & Eng., College Park, MD 20742 USA

For heteroepitaxial growth of perovskite oxide thin films, the accommodation of misfit strain and the generation of structural defects have been major research focuses. Recently the defect structure and misfit accommodation of a 350-nm-thick epitaxial Ba<sub>0.3</sub>Sr<sub>0.7</sub>TiO<sub>3</sub> (BSTO) film grown on (001) LaAlO<sub>3</sub> have been investigated by means of detailed conventional and high resolution electron microscopy (HREM). The film was prepared by pulsed laser deposition from two targets BaTiO<sub>3</sub> and SrTiO<sub>3</sub>. Employing two targets is useful for fabricating compositional spread for combinatorial research. The predominant defects in the film are a high density of edge-type threading dislocations (TDs) with Burgers vectors  $b = \langle 100 \rangle$  and  $\langle 110 \rangle$ . Pure-screw TDs and partial TDs with mixed character were also observed. A remarkable reduction in defect density was found within the first 100nm BSTO adjacent to the interface. In the top layer, almost all TDs with  $b = \langle 100 \rangle$  are perfect, while TDs with  $b = \langle 110 \rangle$  usually split into two partials having  $b = \frac{1}{2}\langle 110 \rangle$ . Only a low density of stacking faults (SFs) with short extension (a few nm) were observed. Within the first 100nm of the film, however, many of the TDs with  $b = \langle 100 \rangle$  split into two or three partials. More interestingly, a high density of extended SFs with displacement vectors  $R = \frac{1}{2}\langle 110 \rangle$  were observed. The faults lie mostly on the {100} planes and occasionally on {110}. The SFs with  $R = \frac{1}{2}[101]$  on (110) or (1-10) have never been observed before in perovskites. Various possible atomic configurations of the faults were considered. The atomic structure of the SFs having two edge-sharing TiO<sub>6</sub> octahedron layers was suggested according to HREM simulation. Electron spectroscopic imaging shows that the faults are Ti-rich, in support of the structure model. A small amount of excess TiO<sub>2</sub> during the film deposition favored the formation of the extended SFs, which was enhanced by the misfit-induced compressive strain during the early stage of the film growth. The lattice mismatch (-4%) between BSTO/LaAlO<sub>3</sub> is mostly accommodated by short segments of misfit dislocations (MDs) running along  $\langle 100 \rangle$ . Many MDs are perfect edge dislocations, while dissociated MDs are frequently observed. Some partial MDs have Burgers vectors with in-plane screw components and others with out-of-plane components. The MD segments are not necessarily located at the interface but have some heights from it. The strain distribution in the first 100nm BSTO close to the interface is not homogeneous. But it was adjusted by the propagation of the SFs and TDs, which finally gave rise to an almost strain-free area in the upper layer of the film.

8:40 AM

**EE2, Stresses and Defects in Thin-Film Barium-Strontium Titanates—Effects on Ferroelectric Properties:** *Davor Balzar*<sup>1</sup>; Padmanabhan A. Ramakrishnan<sup>2</sup>; Sughantha Mani<sup>2</sup>; Allen M. Hermann<sup>2</sup>; Priscila Spagnol<sup>3</sup>; <sup>1</sup>University of Denver, Dept. of Physics & Astron., 2112 E. Wesley Ave., Denver, CO 80208 USA; <sup>2</sup>University of Colorado, Dept. of Physics, PO Box 390, Boulder, CO 80309 USA; <sup>3</sup>Chemistry Institute, UNESP, Chem., CEP 14801-970, Araraquara, SP 14801-970 Brazil

Ferroelectrics are considered for uses in different microelectronics applications, such as integrated, nonvolatile and dynamic random access memories, pyroelectric detectors, acoustic transducers, and microwave tunable devices (phase shifters, resonators, filters, etc.). In these applications ferroelectric, nonlinear dielectric, pyroelectric, and piezoelectric properties are all being exploited. Residual stresses and defects play an important role in shaping properties of thin films. The dielectric, ferroelectric, thermodynamic, mechanical, and optical properties of ferroelectric thin films can be substantially altered as compared to the bulk material. In particular, the epilayer-substrate misfit, chemical composition, deposition conditions, post-deposition annealing, and different thermal-expansion coefficients result in a varying degree of residual stress, dislocation, and point-defect density. However, to date, beyond some empirical data, there is little understanding of microstructure-properties relationship in these materials and a comprehensive theoretical model is lacking. One of the most promising materials is  $Ba_{1-x}Sr_xTiO_3$  system because of its high permittivity, chemical and mechanical stability, simple crystal structure, and easy tuning of ferroelectric transition temperature by a Sr/Ba composition adjustment. To systematically study how stresses and defects affect particularly the dielectric permittivity, the ferroelectric-transition temperature, and dielectric losses, we prepared by the pulsed-laser deposition two series of thin films: In the first,  $Ba_{0.5}Sr_{0.5}TiO_3$  thin films were grown on the  $LaAlO_3$  substrate under different deposition conditions; in the second, we doped  $Ba_{0.6}Sr_{0.4}TiO_3$  thin films with 1% W and Mn, with the expectation that the dopants targeted at the Ti site will influence the oxygen-vacancy concentration. Dielectric and ferroelectric properties were determined by the capacitance measurements and x-ray diffraction was used to determine both residual strains and defect densities by analyzing diffraction line shifts and line broadening, respectively. We found that both elastic strains and defect densities are affected by different preparation conditions and doping. This correlates with the change in relative permittivity and ferroelectric-transition temperature and can qualitatively explain changes in dielectric loss. To explain the experimental findings, we model the dielectric and ferroelectric properties of interest in the framework of Landau-Ginsburg-Devonshire thermodynamic theory. As expected, an elastic-strain contribution due to the epilayer-substrate misfit has an important influence on the free-energy. However, additional terms that correspond to the inelastic strain component had to be introduced to fully explain the measurements.

9:00 AM

**EE3, Intrinsic Bipolar Doping in Transparent Conductive Oxides:** *Xiliang Nie*<sup>1</sup>; Su-Huai Wei<sup>1</sup>; S. B. Zhang<sup>1</sup>; <sup>1</sup>Computational Materials Science Group, Natl. Renewable Energy Lab., 1617 Cole Blvd., Golden, CO 80401-3393 USA

Doping wide-gap materials  $p$ -type is highly desirable but often difficult. It is even difficult to have bipolar doping (both  $n$ -type and  $p$ -type doping) in transparent conductive oxides. This makes the recent discovery of  $p$ -type delafossite oxides,  $CuM^{III}O_2$ , very attractive. The  $CuM^{III}O_2$  also show unique and unexplained physical properties. 1) Band gap of  $CuM^{III}O_2$  increases from  $M^{III}=Al, Ga, to In$ , that is in opposite trend of conventional group III containing semiconductors. 2) The bipolar doping had been observed only in the largest band gap compound  $CuInO_2$  ( $E_g=3.9$  eV) but not in the smaller band gap compounds  $CuAlO_2$  ( $E_g=3.5$  eV) and  $CuGaO_2$  ( $E_g=3.6$  eV). Here, using *ab initio* calculations we reveal that both properties are results of a large disparity between the fundamental electronic gap and the apparent optical gap. Namely, the fundamental direct gap decreases with the increasing of the atomic number from Al, Ga, to In, following the general trend in conventional semiconductors. But the optical band gap (which has been measured in experiments) has a opposite trend due to the fact that the optical transition at the fundamental direct band gap is forbidden as both states have the same parity (even). Furthermore, according to the doping limit rule<sup>1</sup>, compound with low conduction band minimum (CBM) can be doped  $n$ -type more easily whereas compound with high valence band maximum

(VBM) can be doped  $p$ -type more easily. Our calculated band alignment between  $CuM^{III}O_2$  and  $AgInO_2$  show that (a)  $CuInO_2$  has the lowest CBM among the  $CuM^{III}O_2$  compounds (1.48 eV lower than  $CuAlO_2$ ), thus explains why  $CuInO_2$  can be doped  $n$ -type. (b) Due to large coupling between Cu-d and O-p states, the VBM of  $CuM^{III}O_2$  is about 0.7 eV higher than that of  $AgInO_2$ , thus explains the origin of  $p$ -type doping in  $CuM^{III}O_2$ , but only  $n$ -type doping in  $AgInO_2$ . Calculations of defect formation energies confirmed the validity of the doping limit rule in this system. Work was supported by DOE-SC-BES, Contract No. DE-AC36-99GO10337. <sup>1</sup>S. B. Zhang, S.-H. Wei, and A. Zunger, J. Appl. Phys. 83, 3192 (1998).

9:20 AM Student

**EE4, Structural Properties of P-MBE ZnO Films on Sapphire with and without MgO Buffer:** *Agus Setiawan*<sup>1</sup>; Soon K. Hong<sup>1</sup>; Yefan Chen<sup>1</sup>; Hang J. Ko<sup>1</sup>; Jung J. Kim<sup>1</sup>; Takafumi Yao<sup>1</sup>; <sup>1</sup>Tohoku University, Inst. for Matls. Rsrch., 2-1-1 Katahira, Aobaku, Sendai 980-8577 Japan

Structural properties of ZnO films on highly-mismatched  $c$ -plane sapphire grown by plasma-assisted molecular-beam epitaxy with and without MgO buffer layer are investigated. ZnO films with MgO buffer layer are grown two-dimensionally while ZnO films without MgO buffer are grown three-dimensionally as confirmed by RHEED and AFM observations. Types of dislocations, densities, and mosaic spread (tilt and twist angles) in the films are studied by both transmission electron microscopy (TEM) and high-resolution X-ray diffraction (HRXRD). Threading dislocations and mosaic spreads in wurtzite-structure ZnO films have been greatly reduced by dislocation reaction enhanced by introducing the rock salt structure MgO buffer. Screw dislocation densities are dramatically reduced from  $10^{10}$   $cm^{-2}$  to  $10^5$   $cm^{-2}$  range resulting in an extremely small tilt angle of  $0.0056^\circ$ . Edge dislocations are also reduced and it has been investigated that the reduction of dislocations depends on growth conditions of MgO buffer and ZnO films. The results indicate that we can engineer defects in highly mismatched heteroepitaxy using buffer layers.

9:40 AM

**EE5, Hetero-Epitaxial Growth of  $Co_3O_4$  by Low Temperature, Low Pressure MOCVD:** *Anil U. Mane*<sup>1</sup>; Shalini K.<sup>1</sup>; A. Devi<sup>2</sup>; M. Rajeshwari<sup>3</sup>; S. A. Shivashankar<sup>1</sup>; <sup>1</sup>Indian Institute of Science, Matls. Rsrch. Ctr., Bangalore, Karnataka 560012 India; <sup>2</sup>Ruhr-Universität Bochum, Lehrstuhl für Anorganische Chemie II, Bochum D-44780 Germany; <sup>3</sup>University of Maryland, Dept. of Physics, College Park, MD 20742 USA

Normally, the growth of strongly oriented or epitaxial thin films of metal oxides requires relatively high growth temperatures or infusion of energy to the growth surface through means such as ion bombardment. The lattice mismatch between the film and substrate, and crystallographic symmetries—in particular, the details of the arrangement of oxygen atoms in the sublattices—are important in these cases. We have grown high quality epitaxial thin films of  $Co_3O_4$  on different single crystal substrates at a temperature as low as  $400^\circ C$  by low-pressure metalorganic chemical vapor deposition (MOCVD), using cobalt (II) acetylacetonate as the precursor and oxygen as the reactant gas. Polycrystalline  $Co_3O_4$  films are formed on glass and Si(100) in the temperature range  $400$ – $550^\circ C$ . Under the same conditions of growth, highly oriented films of  $Co_3O_4$  are formed on MgO(100) [MGO], SrTiO<sub>3</sub>(100) [STO] and LaAlO<sub>3</sub>(100) [LAO]. The cobalt oxide films were characterized by X-ray diffraction (XRD). XRD  $\theta$ - $2\theta$  scans show that  $Co_3O_4$  films grow with (100), (100) and (110) orientations on MGO, STO, and LAO respectively. The films on MGO, STO, LAO grown at  $450^\circ C$  show X-ray rocking curve (omega-scan) FWHM of  $0.44^\circ$ ,  $0.33^\circ$  and  $1.61^\circ$ , despite a rather large lattice mismatch between film and substrate of 4.1%, 2.3%, and 6.5%, respectively. XRD phi-scan analysis shows cube-on-cube epitaxy on these substrates. The quality of epitaxy on MGO and STO is comparable to the best of the epitaxial perovskite-based oxide thin films grown at significantly higher temperatures. Although the lattice match is better with STO than with MGO, the quality of  $Co_3O_4$  epitaxy on MGO is similar to that on STO. This is explained as being due to the much better match between the oxygen sublattices of  $Co_3O_4$ (100) and MgO(100). It is found that the activation energy for the growth of polycrystalline  $Co_3O_4$  films on glass is significantly higher than that for epitaxial growth on MGO, STO and LAO, though the growth is conducted simultaneously. It is believed that the strong epitaxy results in an especially low activation energy ( $E_a$ ) for growth on MgO (9.5 kJ/mol on MGO vs. 101.2 kJ/mol on glass), because thermal activation is hardly important where growth is promoted strongly by a favorable lattice match. The film microstructure and morphology of the films, analyzed by SEM and AFM, feature faceted grains character-

tic of the cubic symmetry of  $\text{Co}_3\text{O}_4$  on MGO and STO. The faceting is stronger at higher growth temperatures. Due to the structural transition in the LAO substrate at  $\sim 435^\circ\text{C}$ , the growth of  $\text{Co}_3\text{O}_4$  on LAO is complex, and results in a mesh-like morphological formation. A possible mechanism is proposed for the observed low temperature epitaxy on the various single crystal substrates.

10:00 AM Break

## Session FF: Si-Based Heterojunction Growth and Characterization

Friday AM Room: UCEN State Street  
June 28, 2002 Location: University of California

*Session Chair:* Ed Croke, Hughes Research Laboratories,  
3011 Malibu Canyon Rd., RC 63, Malibu, CA 90265-4737 USA

10:20 AM

**FF1, Comparison of Analytical Techniques for Determining Strain Relaxation and Interdiffusion in Strained Si on Relaxed  $\text{Si}_{1-x}\text{Ge}_x$  Heterostructures:** *S. J. Koester*<sup>1</sup>; P. M. Mooney<sup>1</sup>; J. A. Ott<sup>1</sup>; J. L. Jordan-Sweet<sup>1</sup>; J. O. Chu<sup>1</sup>; K. K. Chan<sup>1</sup>; <sup>1</sup>IBM, T. J. Watson Rsrch. Ctr., PO Box 218, Yorktown Heights, NY 10598 USA

Strained Si MOSFETs are of interest for future high-performance logic circuits due to the enhanced electron and hole mobilities that can be achieved. However, CMOS processing conditions can include several high-temperature annealing steps that lead to strain relaxation, misfit dislocation formation and interdiffusion at the Si/Si<sub>1-x</sub>Ge<sub>x</sub> interface. We have studied the thermal stability of strained Si on relaxed Si/Si<sub>1-x</sub>Ge<sub>x</sub> structures annealed at 1000°C using a combination of high-resolution X-ray diffraction (HRXRD), transmission electron microscopy (TEM), and Raman spectroscopy, and compare the suitability of each method for determining strain relaxation and interdiffusion in these structures. The Raman measurements were performed using a confocal microprobe system with an excitation wavelength of 488nm. The HRXRD measurements were performed using a synchrotron X-ray source at NSLS in a triple-axis configuration. Samples with varying Si cap thickness and Ge concentrations were analyzed after annealing for 30 seconds at 1000°C. As expected, greater relaxation occurs for higher Ge mole fraction and for thicker Si layers. However, even in the worst case, very little strain relaxation occurs ( $\sim 10\%$ ). Calculation of the strain relaxation from the misfit dislocation density determined from planar view TEM images showed that even when no strain relaxation was observable by X-ray, some misfit dislocation formation still occurs when the Si cap thickness exceeds the critical thickness for thermodynamic stability. Because of the large experimental uncertainty, Raman spectroscopy showed no detectable trend in the strain relaxation even for the most aggressive annealing conditions. Both the HRXRD and the Raman measurements proved very reliable in determining the degree of interdiffusion at the Si/SiGe interface. The HRXRD results show that no change in the Si cap thickness occurs for annealing times of 5 seconds. For annealing times  $>30$  seconds, the thickness of the Si cap layer decreases with increasing annealing time indicating interdiffusion at the Si/Si<sub>1-x</sub>Ge<sub>x</sub> interface. Within the uncertainty of the measurement, the degree of interdiffusion is found to be independent of the initial Si layer thickness in the range of 7-30nm, as well as the Ge-composition in the range of  $x = 0.19-0.30$ . The Si thickness was determined from the Raman measurements using the ratio of the strained Si peak area to the total fit area. After calibration of the initial thickness with the X-ray results, the Raman analysis of the decrease in layer thickness was in good agreement with the X-ray results with a similar degree of measurement uncertainty. This work emphasizes the requirement for thermodynamically stable heterostructures and/or low temperature device fabrication processes for strained Si CMOS. It also shows that TEM is the most sensitive method to determine defect formation, while Raman spectroscopy could be a useful and high-throughput method for determining interdiffusion effects on Si/SiGe heterostructures. HRXRD is sensitive to both strain and layer thickness, but is unsuitable for routine monitoring as long as a synchrotron source is required.

10:40 AM Student

**FF2, Strained Germanium P-Type and N-Type MOSFETs Fabricated on  $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$  Virtual Substrates:** *Minjoo L. Lee*<sup>1</sup>; Christopher W. Leitz<sup>1</sup>; Arthur J. Pitera<sup>1</sup>; Dimitri A. Antoniadis<sup>2</sup>; Eugene A. Fitzgerald<sup>1</sup>; <sup>1</sup>Massachusetts Institute of Technology, Matls. Sci. & Eng., 77 Massachusetts Ave., Cambridge, MA 02139 USA; <sup>2</sup>Massachusetts Institute of Technology, Electl. Eng. & Compu. Sci., 77 Massachusetts Ave., Cambridge, MA 02139 USA

We have fabricated strained Ge *p*-type and *n*-type metal-oxide-semiconductor field effect transistors (MOSFETs) on relaxed Si<sub>1-x</sub>Ge<sub>x</sub> graded buffers. Poor chemical and mechanical stability prohibits the use of germanium dioxide (GeO<sub>2</sub>) as a gate dielectric for Ge devices, and bulk Ge wafers are not available in the sizes currently used in leading edge Si CMOS fabrication facilities. To accommodate the wafer incompatibility, these Ge-based devices are fabricated on relaxed SiGe grown on Si wafers, and to avoid the use of GeO<sub>2</sub>, a thin epitaxial Si layer is grown on top of the strained Ge channel. The Si cap allows a high quality interface to be formed with a conventional SiO<sub>2</sub> gate and ensures basic compatibility with Si CMOS processing. For strained Ge layers on relaxed SiGe, the valence band is offset from the relaxed virtual substrate below the channel and the Si above, resulting in a well for holes. Furthermore, compressive strain reduces the hole effective mass and lifts the valence band degeneracy in Ge. In our devices, Ge layers were grown on relaxed Si<sub>1-x</sub>Ge<sub>x</sub> ( $x=0.7$  to 1.0) and capped with Si in all cases. The high Ge content in the virtual substrate results in 2.8% to 4% lattice mismatch for the Si layer, and considerable relaxation ensues as the cap is grown. Despite the defects in the Si layer, significant mobility enhancements for the *p*-MOSFETs were measured for all virtual substrate compositions, demonstrating the concept of Si as a universal cap material for a wide range of lattice constants. A sample with a 115 Å Ge channel grown on a Si<sub>0.3</sub>Ge<sub>0.7</sub> virtual substrate exhibited hole mobility enhancements greater than 8 times over bulk Si. Further, by holding the Si cap thickness at 50Å or less, the hole mobility enhancement could be completely preserved at a wide range of vertical effective fields. The conduction band in the strained Ge MOSFET differs from the valence band, because the type-II band alignment of the strained Ge and Si cap forms a well at the surface for electrons. *n*-MOSFETs consisting of a 60Å strained Ge layer grown on a Si<sub>0.3</sub>Ge<sub>0.7</sub> virtual substrate and capped with 45Å of Si exhibit electron mobility enhancements of 1.50 ( $\pm 0.15$ ) times over bulk Si. Recently published findings show that a surface strained Si layer as thin as 50Å can completely contain the electron wave function, meaning that the electron experiences minimal conduction through the strained Ge channel below. The observed mobility enhancement indicates that a high density of defects in the surface layer does not preclude high electron mobility. Strategies for increasing electron occupation in the strained Ge layer will be presented, as well as the effects of strain and Si cap thickness on electron mobility.

11:00 AM Student

**FF3, The Role of Defects on Heat Conduction in Si and Ge Based Superlattices:** *Scott Huxtable*<sup>1</sup>; Alexis R. Abramson<sup>2</sup>; Woo Chul Kim<sup>1</sup>; Arun Majumdar<sup>1</sup>; Gehong Zeng<sup>3</sup>; John E. Bowers<sup>3</sup>; Ali Shakouri<sup>4</sup>; Edward T. Croke<sup>5</sup>; Channing C. Ahn<sup>6</sup>; <sup>1</sup>University of California–Berkeley, Mechl. Eng., 5107 Etcheverry Hall, Berkeley, CA 94720 USA; <sup>2</sup>University of California–Berkeley, Mechl. Eng. Dept., 131 Hesse Hall, Berkeley, CA 94720 USA; <sup>3</sup>University of California–Santa Barbara, Electl. & Compu. Eng., Rm. 4163, Eng. I, Santa Barbara, CA 93106 USA; <sup>4</sup>University of California–Santa Cruz, Electl. Eng. Dept., 253A, Jack Baskin Sch. of Eng., Santa Cruz, CA 95064 USA; <sup>5</sup>HRL Laboratories, LLC, Malibu, CA 90265 USA; <sup>6</sup>California Institute of Technology, Matls. Sci., 233 Keck Lab., Pasadena, CA 91125 USA

The thermal conductivity of semiconductor superlattices is an important parameter for the performance of thermoelectric devices. Recently, numerous studies have reported thermal conductivity of several superlattice systems including GaAs/AlAs, Si/Ge, Si/SiGe, and Bi<sub>2</sub>Te<sub>3</sub>/Sb<sub>2</sub>Te<sub>3</sub>. In several cases the thermal conductivity of the superlattice was found to be below the value of a comparable alloy of the same materials. While this reduction in thermal conductivity has been attributed to a variety of mechanisms including defect scattering, mini-bandgap formation, and interface scattering due to mismatches in phonon spectra and acoustic impedance, the specific reasons remain unclear. One major deficiency in much of the previous work is that there has been little effort to correlate the quality of the growth of the superlattices with the thermal



conductivity data. Without knowledge of the quality of the interfaces and the possible presence of defects, it is difficult to determine the relative importance of defect scattering in relation to thermal conductivity reduction in superlattices. This is particularly important in the growth of lattice mismatched systems, such as Si and Ge, where one could expect a significant number of defects in the growth of the superlattices. Recently, we measured the thermal conductivity of several Si/Si<sub>1-x</sub>Ge<sub>x</sub> superlattices and found that for the Si/Si<sub>0.7</sub>Ge<sub>0.3</sub> samples, the thermal conductivity decreased for decreasing period thickness (increasing number of interfaces). For these four samples, the additional interfaces seemingly added a corresponding thermal boundary resistance. Furthermore, the Si/Si<sub>0.4</sub>Ge<sub>0.6</sub> superlattice exhibited a 70% reduction in thermal conductivity when compared to a Si/Si<sub>0.7</sub>Ge<sub>0.3</sub> superlattice with the same period. Obviously, the interfaces play an important role in these samples, yet it is not clear if this additional interfacial resistance is due to acoustic impedance mismatch, scattering by defects induced by the growth of lattice mismatched layers, or some other mechanism. For example, the Si/Si<sub>0.4</sub>Ge<sub>0.6</sub> sample has a larger acoustic impedance mismatch than the Si/Si<sub>0.7</sub>Ge<sub>0.3</sub> sample since it has a larger Ge fraction in the SiGe alloy. However, there is also a greater mismatch of the lattice parameters in the Si/Si<sub>0.4</sub>Ge<sub>0.6</sub> sample because of that larger Ge fraction. This larger lattice parameter presumably could lead to more defects. Currently, we are in the process of characterizing the growth quality of these samples via X-ray diffraction and transmission electron microscopy (TEM). This should allow for some insight regarding the importance of defects on thermal conductivity. Additionally, work is underway to optimize the growth process such that similar superlattices with the same acoustic impedance mismatch can be grown with fewer defects than the samples measured previously, which would further clarify the relative importance of defect scattering and acoustic impedance mismatch.

11:20 AM

**FF4, Formation of High Quality Silicide on SiGe with High Ge Contents:** C. Y. Lin<sup>1</sup>; C. H. Lai<sup>1</sup>; C. W. Chen<sup>2</sup>; Albert Chin<sup>1</sup>; <sup>1</sup>National Chiao Tung University, EE, 1001 Ta Hsueh Rd., Hsinchu 300 Taiwan; <sup>2</sup>Huwei Institute of Technology, Mech. Eng., 1001 Ta Hsueh Rd., Hsinchu 300 Taiwan

SiGe pMOSFET has attracted much attention recently because it can enhance the hole mobility that is important for high-k gate dielectrics and can extend the VLSI scaling trend. Using the high temperature stable SiGe, ultra-thin gate oxide grown on SiGe can achieve comparable quality with that on Si. However, forming high quality silicide on SiGe is a difficult challenge because strong agglomeration is found that degrades the contact resistance and leakage current. In this study, we have compared the Ni and Co silicides on both n-type and p-type SiGe/Si. After forming single crystal Si<sub>0.7</sub>Ge<sub>0.7</sub> or Si<sub>0.6</sub>Ge<sub>0.4</sub> on Si by solid-phase epitaxy, we have implanted the SiGe/Si by 10 KeV B+ or 50KeV As+ to form source-drain P+N or N+P junctions. Then Ni:SiGe or Co:SiGe were formed subsequently by two step RTA from 350°C to 700°C or 500°C to 900°C, respectively. The formation of silicide is confirmed by XRD where a poly-crystalline silicide is formed. The measured sheet resistance indicate that Ni silicide is much better than Co silicide on either Si<sub>0.3</sub>Ge<sub>0.7</sub> or Si<sub>0.6</sub>Ge<sub>0.4</sub>. A very low sheet resistance of 5 ohm/sq is achieved by Ni silicide at a low silicidation temperature of 400°C and stable until the temperature up to 700°C. This result suggests that excellent thermal stability and large process margins of silicide can be obtained if the Ni is used. Similar phenomenon was also observed in Ni silicide on poly SiGe gate that is important for reducing gate depletion. Very low source-drain junction leakage current less than 4 fA/μm<sup>2</sup> in both N+/P and P+/N junctions are measured that indicates the excellent silicide quality with very low Ni penetration. We have used cross-sectional TEM to further exam the Ni silicide and the observed smooth Ni:Si<sub>0.3</sub>Ge<sub>0.7</sub> thin film is the reason to led to low junction leakage current and low sheet resistance. The good Ni silicide integrity on SiGe provides additional step to realize SiGe MOSFET in the near future.

11:40 AM Student

**FF5, Nickel Silicidation Techniques for Strained Si<sub>1-x</sub>Ge<sub>x</sub>/Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub>/Si<sub>1-y</sub>C<sub>y</sub> Alloys:** Z. Shi<sup>1</sup>; D. Onsongo<sup>1</sup>; X. Chen<sup>1</sup>; S. Banerjee<sup>1</sup>; <sup>1</sup>The University of Texas at Austin, Electr. & Compu. Eng., Austin, TX, 78758 USA

Metal silicides, including Ni silicide, are attractive for microelectronic applications. Strained Si<sub>1-x</sub>Ge<sub>x</sub> alloys are very promising for future CMOS and HBT technology. Si<sub>1-x</sub>Ge<sub>x</sub>, Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub>, and Si<sub>1-y</sub>C<sub>y</sub> can be used as gate materials, elevated source/drain, or channels in MOSFETs. Hence

a good silicide material for Si<sub>1-x</sub>Ge<sub>x</sub>, Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub>, and Si<sub>1-y</sub>C<sub>y</sub> alloy materials is needed. Compressively strained Si<sub>1-x</sub>Ge<sub>x</sub>, Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub>, and Si<sub>1-y</sub>C<sub>y</sub> were grown by UHVCVD. Ni and TiN were deposited at a base pressure of less than 2×10<sup>-7</sup> Torr. A TiN layer was used as a cap to prevent Ni from reacting with O<sub>2</sub> in air. Samples were annealed in N<sub>2</sub> ambient at different temperatures for 30s in a RTA system. After silicide formation, sheet resistance was measured using automatic resistivity probe. Film phase identification and thickness was performed by HRTEM, and chemical composition was determined by XPS and RBS. Samples with 400Å Si<sub>0.8</sub>Ge<sub>0.2</sub>, 1200Å Si<sub>0.8</sub>Ge<sub>0.2</sub>, 400Å Si<sub>0.65</sub>Ge<sub>0.35</sub>, 400Å Si<sub>0.8</sub>Ge<sub>0.2</sub> with 40Å Si cap, 400Å Si<sub>0.785</sub>Ge<sub>0.2</sub>C<sub>0.015</sub>, and 350Å Si<sub>0.985</sub>C<sub>0.015</sub> grown on Si substrates, as well as Si control samples were studied for potential planar/vertical MOSFETs or HBT applications. The sheet resistance as a function of RTA temperature for all the samples is shown in figure 1. Low resistivity phase silicide has been obtained for all the samples with different low sheet resistance temperature windows. The fact that the electrical results are similar for both 400Å and 1200Å Si<sub>0.8</sub>Ge<sub>0.2</sub> samples shows that the thickness of the Si<sub>1-x</sub>Ge<sub>x</sub> layer is not significant as long as the Si<sub>1-x</sub>Ge<sub>x</sub> layer is enough for silicide consumption. The fact that 400Å Si<sub>0.785</sub>Ge<sub>0.2</sub>C<sub>0.015</sub>, 400Å Si<sub>0.8</sub>Ge<sub>0.2</sub>, 400Å Si<sub>0.65</sub>Ge<sub>0.35</sub> samples show smaller low sheet resistance temperature windows than Si indicates that alloy film relaxation and resulting dislocation could result in high sheet resistance. Critical thickness of Si<sub>1-x</sub>Ge<sub>x</sub> decreases with increasing Ge concentration, however with addition of C, the alloy is more thermally stable. The result in terms of low sheet resistance temperature window and sheet resistance for Si<sub>0.985</sub>C<sub>0.015</sub> sample is close to that of Si. This result is expected since C concentration is only 1.5% and the alloy layer is relatively thin, and therefore the sample is very thermally stable. HRTEM results for Si and 400Å Si<sub>0.8</sub>Ge<sub>0.2</sub> samples are shown in figure 2. The silicide layer is about 150-180Å with good crystallinity. The silicide surface and interface were quite smooth, and the silicide film was quite uniform. The resistivity is 12.5-18.9 μΩ-cm based on measured sheet resistance. The XPS and RBS results confirm that a thin layer of low resistivity silicide was formed. Ni atomic percentage in silicide layer for both Si and 400Å Si<sub>0.8</sub>Ge<sub>0.2</sub> samples at the same RTA condition (500°C 30s) is approximately 50%. Therefore the mechanism to form NiSi<sub>1-x</sub>Ge<sub>x</sub> silicide could be analogous to that of NiSi.

12:00 PM

**FF6, Growth of CaF<sub>2</sub>/Si/CaF<sub>2</sub> Resonant-Tunneling Structures:** B. H. Mueller<sup>1</sup>; C. R. Wang<sup>1</sup>; K. R. Hofmann<sup>1</sup>; <sup>1</sup>University of Hannover, Inst. of Semiconductor Devices & Elect. Matls., Appelstr. 11A, Hanover 30167 Germany

The integration of silicon-based resonant tunneling structure into future silicon-based integrated circuits opens exciting possibilities for reduction of circuit complexity and new device functions. Epitaxial CaF<sub>2</sub>/Si/CaF<sub>2</sub> double-barrier structures on Si substrates are highly attractive candidates for resonant-tunneling diodes (RTDs) due to the large conduction-band discontinuity and small lattice mismatch at the insulator/semiconductor hetero-interface. The realization of such devices requires the growth of both very thin, atomically flat CaF<sub>2</sub> layers on Si and of Si on CaF<sub>2</sub> with abrupt interfaces and a minimum of defects. Growth of CaF<sub>2</sub> on Si (111) has been extensively studied, and atomically flat CaF<sub>2</sub> films have been achieved. The epitaxial growth of Si on CaF<sub>2</sub>, however, has been less investigated and is more difficult to achieve because the smaller surface free energy of CaF<sub>2</sub> makes wetting of the CaF<sub>2</sub> surface with Si energetically very unfavorable. This investigation concentrated on the MBE growth of nanometer Si films on CaF<sub>2</sub>/Si(111) substrates at various temperatures and subsequent annealing steps to produce high-quality CaF<sub>2</sub>/Si/CaF<sub>2</sub> double-barrier structures. CaF<sub>2</sub>/Si/CaF<sub>2</sub> RTDs on Si substrates were fabricated and current voltage (I-V) characteristics with negative differential resistance (NDR) were observed. As expected the growth at elevated temperatures leads to non-wetting, and islanding of the Si due to the high mobility of Si on well oriented CaF<sub>2</sub> surfaces. The sizes of and distance between the islands increase with temperature. An approach to overcome the thermodynamical limitations is the deposition of a Si film at room temperature and recrystallization at elevated temperature. The surface morphology of Si films is strongly improved, as seen by RHEED and AFM measurements. Finally, a 1.5nm(top)CaF<sub>2</sub>/2.8nm Si/1nm CaF<sub>2</sub> double barrier stack was grown in oxide windows, which have been generated ex vacuo on 4 inch n+-Si(111) wafers. The first 1nm CaF<sub>2</sub> barrier was evaporated at 500°C using a standard effusion cell. The 2.8nm Si quantum well was deposited close to room tempera-



ture, followed by the growth of 1.5nm CaF<sub>2</sub> top barrier layer at the same temperature. Immediately after unloading from the UHV growth chamber, a 200nm Al film was evaporated and patterned to form the electrodes. Prior to the electrical characterization the diodes were annealed for 10min at 450°C in a forming gas (10%H<sub>2</sub> /90%N<sub>2</sub>) atmosphere. The I-V characterization of the diodes was performed at three temperatures from 77K to room temperature, with a continuous voltage source. At about 0.65V a resonant tunneling peak is visible. Between 77K and 140K we could not observe any shift of the peak position. However, the I-V characteristic is superposed by an approximately exponentially increasing leakage current. A surprisingly high peak current density of 5x10<sup>-4</sup>A/cm<sup>2</sup> could be inferred after correcting for this leakage current.

## Session GG: Semiconductors: Processing and Oxidation

Friday AM                      Room: UCEN Harbor  
June 28, 2002                Location: University of California

*Session Chairs:* Doug Hall, University of Notre Dame, 260 Fitzpatrick Hall, Notre Dame, IN 46556 USA; K. Y. Norman Cheng, University of Illinois at Urbana-Champaign, Elect. & Compu. Eng. Dept., 150 Microelect. Lab., 208 N. Wright St., Urbana, IL 61801 USA

### 8:20 AM Student

**GG1, Chemical and Structural Characterization of GaSb (100) Surfaces Treated by HCl-Based Solutions and Annealed in Vacuum:** *Zhiyan Liu*<sup>1</sup>; Brian Hawkins<sup>1</sup>; Thomas F. Kuech<sup>1</sup>; <sup>1</sup>University of Wisconsin-Madison, Dept. of Cheml. Eng., 1415 Engineering Dr., Madison, WI, 53706 USA

GaSb is used as a substrate for the epitaxial growth of many of the 6.1Å binary and alloy semiconductors. The very chemically reactive nature of GaSb leads to the rapid oxidization of its surface upon exposure to air with a chemically robust and thick native oxide being formed on the surface. Preparation of a flat and oxide-free substrate surface, on the atomic level, is therefore a critical step for the use of these substrates in epitaxial growth applications and in the development of GaSb-based devices. The development of a reproducible, uniform and efficient surface preparation process has been difficult in the case of GaSb. In this work, several cleaning processes based on HCl have been studied. The modification of surface properties such as oxide layer thickness, surface stoichiometry and surface roughness are characterized by X-ray photoelectron spectra(XPS) and atomic force microscopy(AFM). XPS analysis of GaSb with native oxides on the surface indicates that the thickness of the native oxide grown at room temperature is about 3~5nm, consisting of both Ga<sub>2</sub>O<sub>3</sub> and Sb<sub>2</sub>O<sub>3</sub> throughout the oxide layer with elemental Sb present at the oxide-GaSb interface. Comparison of the overall peak intensities associated with antimony and gallium indicate that the surface layer is slightly gallium-rich due to its higher electronegativity. The native oxide thickness was found to be reduced to 1~2nm, with a substantial reduction in the surface roughness, after dipping the substrate in concentrated HCl for 5 minutes and subsequently rinsing in 2-propanol. If the substrate is rinsed in DI-water after being dipped in the HCl solution, the Ga<sub>2</sub>P<sub>3</sub> spectra obtained from XPS measurements are shifted to higher binding energies. This shift is associated with an additional gallium chemical species on the surface, formed due to exposure to the water rinse. AFM images reveal a high density of small rounded morphological features on the sample surface after chemical treatment. The density and size of these features grow rapidly upon exposure to air after the treatment and are associated with the subsequent formation of a renewed surface oxide layer. An additional chemical treatment was also studied: the substrate is first cleaned in concentrated HCl for 5 minutes, then dipped into another solution composed of tartaric acid(20g)+H<sub>2</sub>O<sub>2</sub>(40ml)+HF(2ml)+DI water(600ml) for 24 seconds, finally rinsed by deionized water. A thicker overlayer was found with the overall intensity of antimony to gallium being only 0.32 indicating that the highly nonstoichiometric overlayer is dominated by gallium species.

The reaction and desorption of surface oxides were studied by thermal annealing of the substrate in vacuum after specific chemical treatment. XPS results show that the desorption temperature for Sb<sub>2</sub>O<sub>3</sub> is ~350°C and ~500°C for Ga<sub>2</sub>O<sub>3</sub>. The surface becomes oxide-free after thermal annealing in vacuum for 30 minutes at 600°C.

### 8:40 AM

**GG2, Effective GaAs Surface Passivation by N<sub>2</sub>-H<sub>2</sub> Remote Plasmas:** M. Losurdo<sup>1</sup>; M. Ambrico<sup>1</sup>; P. Capezzuto<sup>1</sup>; *G. Bruno*<sup>1</sup>; <sup>1</sup>Istituto di Metodologie Inorganiche e Plasmochimiche, CNR-IMIP, via Orabona, Bari 4-70126 Italy

An intensive research on the passivation techniques for GaAs surfaces exists to develop a technology based on GaAs metal-insulator-semiconductor (MIS) devices. Plasma nitridation of GaAs surfaces has been investigated to form a thin layer of high band gap GaN to stabilize and passivate the GaAs surface. Nevertheless, contradictory results have been reported about its effectiveness, since plasma-induced damage is seen as the cause of interface states, which probably lead to Fermi-level pinning and degradation of J-V characteristics of GaAs/GaN based Schottky diodes. However, in the previous studies, except the detection of Ga-N bonds formation, no attention has been devoted to the nitridation chemistry and to the effect of the nitrided layer thickness and of the GaAs/GaN interface composition on the passivation effectiveness. The lack of ability to control GaAs/insulator and in particular GaAs/GaN interface has resulted in a reduction of attempts to develop a GaAs MIS technology. In this contribution, we present results on the use of N<sub>2</sub>-H<sub>2</sub> and N<sub>2</sub> remote radio frequency (RF) plasma nitridations of GaAs (100) surfaces performed to investigate the effect of the nitridation chemistry, i.e. the GaAs/GaN interface composition, and of the GaN thickness on the quality of the electronic passivation of GaAs surfaces. Spectroscopic ellipsometry (SE) is used to control in real time the thickness of the GaN layer and the chemistry of the GaAs/GaN interface. Photoluminescence and evaluation of the ideality factor and true barrier of Schottky diodes. In particular, it is found that N<sub>2</sub> plasma nitridation yields As segregation at the GaAs/GaN interface, and the higher the nitrided layer thickness the higher the As segregation. This could explain the ineffectiveness of the N<sub>2</sub> plasma passivation and the pinning of the Fermi level. In contrast, thin layers (~ 5Å) of GaN obtained by N<sub>2</sub>-H<sub>2</sub> (3% in H<sub>2</sub>) plasma nitridation, result in a very effective GaAs electronic passivation because H-atoms play an important role in the removal of As segregation. A strong increase of the photoluminescence efficiency that is stable over months is found in this case. However, it has been found that a very narrow window in the nitridation time and H-atoms density/exposure exist that are very critical for an effective GaAs electronic passivation. Longer nitridation time that yield a higher GaN thickness, results in Ga-enrichment and, hence, GaAs antisite that pin the Fermi level near the valence band. It is also demonstrated that the GaAs passivation induced by the N<sub>2</sub>-H<sub>2</sub> plasma nitridation is more effective than the conventional GaAs hydrogenation and passivation by sulfur treatments and wet nitridation procedures.

### 9:00 AM

**GG3, Low-Frequency Noise Studies of GaAs-On-Insulator MESFETs:** *Susie Tzeng*<sup>1</sup>; Michael J. Cich<sup>1</sup>; Ri-An Zhao<sup>1</sup>; Henning Feick<sup>1</sup>; Eicke R. Weber<sup>1</sup>; <sup>1</sup>University of California, Dept. of Matls. Sci. & Eng., Berkeley, CA 94720 USA

GaAs-On-Insulator (GOI) layers, obtained by lateral wet oxidation of buried AlGaAs layers, have found widespread application for current confinement in vertical-cavity surface emitting lasers (VCSELs) and have been studied for channel isolation in field-effect transistors (FETs). The oxidation procedure can cause defect injection into the adjacent layers. In particular, carrying out the oxidation longer than needed to achieve full lateral oxidation of the AlGaAs (over-oxidation) is found to have deleterious effects on device performance. Here we study GOI MESFETs using low-frequency noise measurements between 1Hz and 100 kHz. Devices with different gate width were fabricated, resulting in different amounts of over-oxidation. The noise spectra were modeled with a combination of white noise, 1/f noise, and generation-recombination type (Lorentzian) noise. The dependence of the noise spectra on the applied gate and drain biases at different temperatures was investigated in order to determine the origin of the noise. It was found that when the drain current is large enough to neglect gate leakage current the 1/f noise component can be explained by carrier-concentration fluctuations due to a uniform trap-energy distribution at the channel-oxide interface. The effective density of traps was estimated to be 10<sup>11</sup> ~10<sup>12</sup>/cm<sup>2</sup>. Contin-

ued exposure of the oxidation layer to the oxidation ambient resulted in an increase in the trap density. In addition, a clear generation-recombination noise component, with activation energy 0.41eV, was observed when the gate bias was near threshold. The trap responsible for this noise can be related to the defects induced by the oxidation process.

#### 9:20 AM Student

**GG4, Investigation of Digital  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  Alloys ( $x>0.8$ ) for Lateral Oxidation and Regrowth Applications:** Gregory W. Pickrell<sup>1</sup>; Kuo L. Chang<sup>1</sup>; John H. Epple<sup>1</sup>; Kuang C. Hsieh<sup>1</sup>; Keh Y. Cheng<sup>1</sup>; <sup>1</sup>University of Illinois at Urbana-Champaign, Electl. & Compu. Eng., Urbana, IL 61801 USA

With the discovery of lateral oxidation of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  alloys in water vapor, new device structures have been realized. Applications involving vertical-cavity, surface-emitting lasers (VCSELs) and compliant epitaxy of lattice-mismatched layers require strict compositional control to yield reproducible results in both oxidation rate and mechanical stability. These requirements motivated the study of digital alloys, formed by alternating layers of GaAs and AlAs, to form  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layers with high Al content ( $x>0.8$ ). Previously, digital alloys ( $x=0.98$ ) were grown using a repeating structure of 49 monolayers (ML) of AlAs and one ML of GaAs. Lateral oxidation characteristics were compared to true  $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$  alloys and pure AlAs. The digital alloys were found to be superior to their conventional counterparts in both lateral oxidation speed and mechanical stability. At temperatures of 450°C, the oxidation rate of pure AlAs and the digital  $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$  alloy were equal. More importantly, the digital oxide's mechanical stability was superior to the pure AlAs oxide when subjected to post-oxidation processing. Delamination of the oxide layer from the underlying GaAs layers was seen in the pure AlAs material. This effect was minimized using the digital alloys. With an understanding of the mechanisms at work in oxidation of digital alloys, our efforts were directed towards applications involving regrowth of high-quality materials on structures with underlying oxidized layers. Digital  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  alloys were grown using different numbers of ML of AlAs (a) and GaAs (b). Aluminum compositions ranging from 80% to 98% were grown using eight pairs of AlAs/GaAs digital alloy with a composition of a:b equal to 40:10, 45:5, and 49:1 ML resulting in a total  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer thickness of ~1130 Å. These samples were studied to determine the compositional effects on lateral oxidation rate. As with true  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  alloys, decreasing Al content resulted in slower oxidation rates. In addition, the structure used to form a digital  $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$  alloy was varied to determine the effect on lateral oxidation rate. These alloys were formed using a repeated structure of 98:2, 49:1 and 24.5:0.5 ML resulting in a total thickness of ~1130 Å. Finally, regrowths of  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ /GaAs superlattice structures were performed on GaAs layers with underlying oxidized digital alloys as well as oxidized pure AlAs layers. The regrown material was investigated using both optical microscopy and photoluminescence (PL) measurements. After regrowth, a dramatic improvement in the surface morphology, and consequently the useable surface area, was seen using the digital alloys. The PL data also indicate improved material quality for the epilayers grown on structures containing oxidized digital alloys when compared to those grown with oxidized pure AlAs. These results indicate the potential of these alloys for applications involving post-oxidation processing, such as VCSELs, and regrowth of device-quality layers for compliant epitaxy applications.

#### 9:40 AM Student

**GG5, Selective Dry Etching of GaP Over  $\text{Al}_{0.6}\text{Ga}_{0.4}\text{P}$  Using  $\text{SiCl}_4$  and  $\text{SiF}_4$ :** John Epple<sup>1</sup>; Theodore Chung<sup>1</sup>; Concepcion Sanchez<sup>1</sup>; Keh-Yung Cheng<sup>1</sup>; Kuang C. Hsieh<sup>1</sup>; <sup>1</sup>University of Illinois at Urbana-Champaign, Electl. & Compu. Eng., 150 Microelect. Bldg., Urbana, IL 61801 USA

Wide bandgap semiconductors are useful for the production of high power field effect transistors and heterojunction bipolar transistors. However, many of these substrates are extremely expensive and difficult to process. In addition, some of these materials are not available in substrate form with low defect densities. GaP is one wide bandgap material that has been largely overlooked. GaP is relatively inexpensive and can be found in high quality substrates. In addition, GaP based materials have superior processing ease compared to other wide bandgap semiconductors such as GaN. GaN is very hard and is difficult to etch without the use of advanced reactive ion etching (RIE) technologies and physical etching mechanisms. In addition, the need for physical etching assistance has made selective etching between GaN and AlGaN difficult. It will be demonstrated that GaP is etched very easily with etch rates similar to that

of GaAs. With this capability, the possibilities of developing a selective etch are improved. In the GaAs material system, GaAs can easily be selectively etched over AlGaAs by dry etching using a gas mixture containing chlorine and fluorine based gases. It is reported that the fluorine will react with aluminum to form  $\text{AlF}_3$ , which is not etched by chlorine-based gases. Hence  $\text{AlF}_3$  acts as an etch inhibiting layer that may slow or stop the etch.<sup>2</sup> In this study, a selective etching technique has been developed in which GaP can be selectively etched over AlGaP using a mixture of  $\text{SiCl}_4$  and  $\text{SiF}_4$  based gases. Samples used for this study include on-axis (100) GaP substrates and epitaxial  $\text{Al}_{0.6}\text{Ga}_{0.4}\text{P}$  grown by MOCVD. On-axis (100) GaAs substrates are used for a comparison of the etch rate to that of GaP. Etching is performed using a standard RIE chamber. Gases used for the process are  $\text{SiCl}_4$  and  $\text{SiF}_4$ . To study the etching and selective etching of GaP and  $\text{Al}_{0.6}\text{Ga}_{0.4}\text{P}$  several conditions were varied including gas mixture, RF power, and chamber pressure. Increasing the amount of  $\text{SiF}_4$  in the gas mixture increased selectivity between GaP and  $\text{Al}_{0.6}\text{Ga}_{0.4}\text{P}$ . This has only a mild effect on the etch rate of GaP. Higher chamber pressures also have a positive effect on selectivity. GaP was found to have an etch rate as high as 135 nm/min. Under the same conditions GaAs etched at a rate of 142 nm/min demonstrating the etching ease of GaP. Etch selectivity as high as 60 was achieved. As is reported for AlGaAs etching, an  $\text{AlF}_3$  layer is formed on the surface of the  $\text{Al}_{0.6}\text{Ga}_{0.4}\text{P}$  etch stop layer. Presence of this layer is confirmed by Auger electron spectroscopy (AES). AES is also used to show the removal of the  $\text{AlF}_3$  layer by a short dip in a diluted buffered oxide etch solution.

#### 10:00 AM Break

#### 10:20 AM Student

**GG6, Self-Diffusion of Si in Thermally Grown Amorphous  $\text{SiO}_2$ :** Shigeto Fukatsu<sup>1</sup>; Tomonori Takahashi<sup>1</sup>; Kohei M. Itoh<sup>1</sup>; Masashi Uematsu<sup>2</sup>; Akira Fujiwara<sup>2</sup>; Hiroyuki Kageshima<sup>2</sup>; Yasuo Takahashi<sup>2</sup>; Kenji Shiraishi<sup>3</sup>; <sup>1</sup>Keio University, Appl. Physics & Physico-Infomatics, 3-14-1, Hiyoshi, Yokohama 223-8522 Japan; <sup>2</sup>NTT Corporation, NTT Basic Rsrch. Labs., 3-1 Wakamiya, Morinosato, Atsugi 243-0198 Japan; <sup>3</sup>University of Tsukuba, Inst. of Physics, 1-1-1 Tennoji, Tsukuba 305-8571 Japan

One question, which has been raised repeatedly for thermal oxidation of Si, is whether any of excess Si atoms generated at Si/SiO<sub>2</sub> interfaces diffuse into oxide layers and react with oxygen at positions away from the interfaces. For probing of such phenomena, the self-diffusion coefficient D of Si in thermally formed amorphous SiO<sub>2</sub> must be known precisely as a function of the temperature and oxygen partial pressure for dry oxidation. The present work reports the diffusion coefficient D of Si in thermally grown SiO<sub>2</sub> using <sup>nat</sup>SiO<sub>2</sub>/<sup>28</sup>SiO<sub>2</sub> isotope hetero-structures in which <sup>nat</sup>SiO<sub>2</sub> contains 4.7% and 3.1% of <sup>29</sup>Si and <sup>30</sup>Si, respectively, while <sup>28</sup>SiO<sub>2</sub> is depleted of <sup>29</sup>Si and <sup>30</sup>Si isotopes. The structure is composed from top to bottom 50nm-<sup>nat</sup>SiO<sub>2</sub>, 650nm-<sup>28</sup>SiO<sub>2</sub>, 510nm-<sup>28</sup>Si, and 400micron-<sup>nat</sup>Si. Thermal annealings induce diffusion of <sup>29</sup>Si and <sup>30</sup>Si isotopes from the <sup>nat</sup>SiO<sub>2</sub> to <sup>28</sup>SiO<sub>2</sub> layers. Measurements of the <sup>29</sup>Si and <sup>30</sup>Si depth profiles by SIMS and fitting of the data with appropriate error functions allow us to determine precisely D of Si in thermally grown SiO<sub>2</sub>. Thermal annealings have been performed for temperatures 1050-1350°C, durations 30 minutes to 30 days, and oxygen partial pressures P<sub>0</sub>=1-100% in flowing Ar. At least P<sub>0</sub>=1% is needed in order to prevent thermal decomposition of oxide layers. The minimum P<sub>0</sub>~1% is maintained precisely in order to keep the total thickness of oxides unchanged within 3% before and after annealings. For the range P<sub>0</sub>=1-20%, D is independent of P<sub>0</sub> and given by D=200 exp(6eV/kT) cm<sup>2</sup>/sec which turns out to be exactly same for the values reported for bulk fused silica [Acta Metall. 28, 327 (1980)] and quartz [Phys. Rev. Lett. 53, 888 (1988)]. This result is somewhat surprising because silica and quartz are polycrystalline while thermal oxides are amorphous. It shows only the local chemical bonding structures, which are essentially same for polycrystalline and amorphous, determine the thermal diffusivity of Si in SiO<sub>2</sub>. D found in our study is smaller by a factor of 100 than D determined by implantation of <sup>30</sup>Si isotopes into thermal oxides [J. Appl. Phys. 89, 7809 (2001)]. The implantation introduces Si in excess while our method maintains the equilibrium condition throughout the experiment, i.e., the presence of excess Si leads to higher D. Estimation of D indirectly from defect or foreign impurity evolution [Appl. Phys. Lett. 54, 1427 (1989) and 63, 3167 (1993)] lead to values almost 5 orders of magnitudes larger. It shows the difficulty of determining D through those indirect methods. We will discuss at the conference the oxidation partial pressure dependencies of D for the range 20-100%.

10:40 AM

**GG7, Gate Dielectric Formed by Dry Oxidation of Thermal Nitride and its Capability to Prevent Boron Penetration:** *William Wu*<sup>1</sup>; Alex Ku<sup>1</sup>; Jiun-Fang Wang<sup>1</sup>; <sup>1</sup>ProMOS Technologies, Inc., Diffusion Dept., No. 19 Li Hsin Rd., Science-Based Industrial Park, HsinChu, Taiwan

We have proposed an approach to grow thin gate dielectric (28Å) with capability to prevent boron penetration. In this method, gate dielectric is formed by dry oxidation of ultra-thin thermal nitride. Ultra-thin nitride in this process is grown by NH<sub>3</sub> nitridation at high temperature under low pressure. According to SIMS analysis, obvious nitrogen profile with a peak located at dielectric surface can be seen which is quite different from most techniques proposed in the literature. Such nitrogen profile is more promising because it is more resistant to boron penetration to gate dielectric from P+ poly Si electrode and light nitrogen concentration at interface also improves reliability. Furthermore, peak nitrogen concentration could reach as high as 5.11E21 atoms/cm<sup>3</sup>, which is much higher than that of N<sub>2</sub>O treated oxide and comparable with that of oxide grown in NO ambient at high temperature. We deduce that oxygen could diffuse through thin nitride layer and react with Si substrate to form bottom oxide during dry oxidation process. Through such growth mechanism, nitrogen is gradually pushed upward and finally locates at the dielectric surface. In addition to ellipsometer, thickness of thin dielectric is further confirmed by cross-sectional TEM analysis. From TEM characterization, a smooth interface between gate dielectric and Si substrate can also be observed which plays an essential role for device performance. Since it is believed that stress in nitride film would be released when oxygen incorporates, we have performed AFM (atomic force microscopy) for this dielectric to investigate whether the surface roughens during its formation procedure. A measured root mean square (rms) roughness before and after the oxidation is 0.11 and 0.12nm, respectively. This roughness is comparable with that of control oxide (0.09nm). It is worth noticing that the measured even surface is consistent with the smooth and flat interface observed by TEM image. Furthermore, MOS capacitor with P+ poly gate is fabricated to examine the boron retardation capability of this gate dielectric. From the C-V curve, flat band voltage shift toward negative is measured for this dielectric, which could be ascribed to either more positive fixed oxide charge or less penetrated boron from gate electrode. Nevertheless we exclude the possibility that more fixed oxide charge is produced for this dielectric since it has nearly the same flat band voltage as control oxide for MOS capacitor with N+ poly. Therefore this dielectric indeed owns the ability to block boron penetration. To further evaluate its feasibility, gate leakage current and reliability test such as stress induced leakage current (SILC) show comparable results with control oxide and proves promising. Besides possessing many prominent properties, more importantly, this technique is not only easy but also compatible with existent VLSI technologies.

11:00 AM Student

**GG8, Formation of Shallow Junction Using Spin Coating SPD Method for Sub 0.1 Micron SOI MOSFET:** *Kiju Im*<sup>1</sup>; Won-Ju Cho<sup>2</sup>; Seongjae Lee<sup>2</sup>; Sunglyul Maeng<sup>2</sup>; Moon Gyu Jang<sup>2</sup>; Tae Woong Kang<sup>2</sup>; Kyoungwan Park<sup>2</sup>; Hyunsang Hwang<sup>1</sup>; <sup>1</sup>KJIST, Semicond. Integrated Dev. & Proc., Dept. of Matls. Sci. & Eng., Kwangju 500-712 S Korea; <sup>2</sup>ETRI, Telecommunications Basic Rsrch. Labs., Yusong, Taejon 305-600 S Korea

Shallow junction formation has become a major concern for reducing gate length below sub 0.1 micron because device punch-through and short channel effects must be minimized. One of the most promising methods to obtain ultra shallow junction formation is the solid-phase diffusion (SPD) with which we can reduce lattice damages unavoidable in ion implantation process. Although some work has been done on phosphorus there is only few work on arsenic having larger atomic radius as a diffusion source with SPD method. Here we demonstrate the feasibility of SPD for arsenic as well as phosphorus in using sub 0.1 micron MOSFET ultra-shallow source and drain junction. We used the phosphorus doped spin on glass (P-SOG) and As-SOG film formed by simple spin coating method as a diffusion source of highly doped N<sup>+</sup> region. To optimize the junction formation various conditions of RTP processes were performed. In the case of phosphorus the junction depth less than 10nm was possible as evidenced by secondary ion mass spectroscopy profiling. The characteristics of N<sup>+</sup>P diode was saturated around 850°C RTP temperature. The on-off current ratio of the 0.1micron MOSFET using silicon on insulator (SOI) substrate showed excellent

value approximate 10<sup>8</sup>. In the case of arsenic the electrical behavior of N<sup>+</sup>P and 0.1 micron MOSFET is also excellent. In conclusion, spin coating SPD is very effective and simple method to obtain shallow junction including sub 0.1 micron SOI MOSFET source drain junction formation with excellent electrical characteristics.

11:20 AM

**GG9, Late News**

11:40 AM

**GG10, Late News**

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## Session HH: Nanostructures

Friday AM

Room: Corwin West

June 28, 2002

Location: University of California

*Session Chairs:* Rachel S. Goldman, University of Michigan, Matls. Sci. & Eng., 2300 Hayward St., Ann Arbor, MI 48109-2136 USA; Mark Miller, University of Utah, 122 S. Central Campus Dr., Rm. 304, Salt Lake City, UT 84112-0506 USA

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8:20 AM

**HH1, Temperature Dependent Contactless Electroreflectance Study of Intersubband Transitions in a Self-Assembled InAs/InP(001) Quantum Dot Structure:** *Lyudmila Malikova*<sup>1</sup>; Fred H. Pollak<sup>1</sup>; Remo A. Masut<sup>2</sup>; Lev G. Mourkh<sup>3</sup>; <sup>1</sup>Brooklyn College of the City University of New York, NY State Ctr. for Adv. Tech. in Ultrafast Photonic Matls. & Applications, Physics Dept., 2900 Bedford Ave., Brooklyn, NY 11210 USA; <sup>2</sup>Ecole Polytechnique Montreal, Dept. de Genie Physique, Campus de L'universite de Montreal, 2900 boul. Eduard-Montpetit, CP 6079, Succursale Centerville, Montreal, Quebec H3C 3A7 Canada; <sup>3</sup>Stevens Institute of Technology, Dept. of Physics & Eng. Physics, Hoboken, NJ 07030 USA

During the past decade there has been considerable fundamental and applied interest in quantum dots (QDs) due to their electronic properties and their potential for device applications. Self-assembled InAs QDs on InP(001) substrates exhibit room temperature photoluminescence (PL) in the range of 1.6 μm, convenient for telecommunication applications. Presently there are no reports on the characterization of InAs/InP QDs by contactless electroreflectance (CER), which compared to PL can measure transitions above the fundamental resonance and which can also be performed in a wide temperature range. Furthermore, there are no reports on systematic investigations of the temperature dependence of the energies involved in QD transitions. We report the temperature variation (17K<T<325K) of the energies of the two observed excitonic intersubband transitions from the QDs which is similar to that for III-V semiconductors, both bulk and quantum wells (QW). In contrast the temperature dependence of the broadening parameters was quite different for QDs. The self-assembled QD structure was grown by metal-organic vapor phase epitaxy in a Stranski-Krastanov mode on (001) InP substrate using trimethylindium, tertiarybutylarsine and phosphine as precursors and hydrogen as the carrier gas. The InAs growth temperature is 500C which gives a distribution of nanometer-sized islands (near 30nm diameter) on an InAs wetting layer (WL) of approximately 2 monolayers (ML). The CER spectra at all temperatures exhibit features from the QDs (Q<sub>11</sub>, Q<sub>22</sub>), the WL and the InP buffer layer and substrate. The QD part of the spectrum was fitted to the first derivative of a Lorentzian functional form, which is appropriate for an excitonic transition and yields the energies (E<sub>11</sub> and E<sub>22</sub>) and broadening parameters. We obtained numerically the envelope functions and eigen energies for electrons and holes in the effective mass approximation including strain effects. It was found that Q<sub>11</sub> and Q<sub>22</sub> correspond to the first electron-first heavy hole and second electron-second heavy hole transitions in the disk plane, respectively. We have fit the temperature dependence of the energies of the Q<sub>11</sub>, Q<sub>22</sub> transitions as well as the WL and InP to both Varshni and Bose-Einstein type expressions. For the InP peak the obtained parameters are in reasonable agreement with previous measurements. We cannot compare the parameters of E<sub>11</sub> and E<sub>22</sub> to bulk InAs since there is no reliable

data for the bulk material. However, their temperature behavior seems in general agreement with reported III-V bulk and QW transitions. Although the two features from the QDs narrow with decreasing temperature the details of the temperature dependence of the broadening is different from that of III-V bulk and QWs, i.e. a Bose-Einstein-like behavior related to the  $q = 0$  LO phonon.

#### 8:40 AM Student

**HH2, Structural and Optical Characterization of Rapid-Thermal-Annealed InAs/In<sub>0.15</sub>Ga<sub>0.85</sub>As DWELL Dots Using X-Ray Diffraction and Photoluminescence:** Sunil Raghavan<sup>1</sup>; Allen L. Gray<sup>2</sup>; Andreas Stintz<sup>1</sup>; Kevin Malloy<sup>1</sup>; *Sanjay Krishna*<sup>1</sup>; <sup>1</sup>University of New Mexico, Electl. & Compu. Eng., Ctr. for High Tech. Matls., Albuquerque, NM 87106 USA; <sup>2</sup>Zia Laser, Inc., 801 University Blvd. SE, Albuquerque, NM 87106 USA

Self-assembled InGaAs/GaAs quantum dots have emerged as a very important material system for their application in optoelectronic devices and for the unique physics that exists in these quasi-zero dimensional ensembles. In-situ and ex-situ anneals have been employed to study the effect of interdiffusion in quantum dot ensembles and to alter the optical properties in these samples. However, all the studies undertaken so far have been performed on (In,Ga)As dots with GaAs barriers. There has been very little work reported on the effect of annealing on the technologically important InAs/InGaAs dots-in-well (DWELL) system. The study of annealing on this system is also very interesting from the materials point of view since the InGaAs well could serve as a barrier for the outdiffusion of In from the InAs dots. Moreover, the quality of the InGaAs well can be very well monitored using double crystal X-ray diffraction (DCXRD). In this paper, we study the effect of rapid thermal annealing (RTA) on a 10-layer InAs/In<sub>0.15</sub>Ga<sub>0.85</sub>As DWELL dots grown by molecular beam epitaxy. Photoluminescence (PL) measurements on these dots reveal a blue shift of about 111 meV between the sample annealed at 750°C and the as-grown sample with a reduction in the PL linewidth. There was a significant decrease in the PL intensity with increase in the anneal temperature, which could be due to relaxation in the strained dots or the wells. Further studies were undertaken using DCXRD. In the X-ray rocking curves for a symmetric (004) scan, a gradual shift in the zeroth order peak towards the GaAs substrate peak indicates a decrease in the lattice constant in the growth direction, possibly due to In/Ga interdiffusion. This explains the blue shift observed in the PL spectra. The shift in the zeroth order peak also suggests an onset of relaxation in the dots that could lead to the observed decrease in the PL intensity. The decrease in the linewidth of the satellite peaks in the X-ray curves till Ta=750°C is possibly due to the homogenization of the dot distribution by In/Ga interdiffusion, which also explains the decrease in the linewidth of the PL spectra. However, as the temperature is increased beyond 750°C, the FWHM of both the X-ray and the PL spectra increase. Till Ta=800°C, a large number of pendellosung oscillations with uniform linewidths are observed suggesting good compositional uniformity in the dots-in-well. At Ta=850°C, the number of pendellosung oscillations decreases indicating the degradation of the quantum well-barrier interface and the possible dissolution of the dots as no PL was observed from the dots at this temperature. The excellent correlation obtained between the DCXRD and PL measurement will be discussed in the presentation.

#### 9:00 AM

**HH3, Characterization of InAs Surface Quantum Dots Grown on GaAs by Metalorganic Chemical Vapor Deposition:** *Abdel-Rahman A. El-Emawy*<sup>1</sup>; Allen L. Gray<sup>2</sup>; Diana L. Huffaker<sup>1</sup>; <sup>1</sup>University of New Mexico, Ctr. for High Tech. Matls., 1313 Goddard SE, Albuquerque, NM 87106 USA; <sup>2</sup>Zia Laser, Inc., Crystal Growth, 801 University Blvd. SE, Albuquerque, NM 87106 USA

We discuss formation trends and characterization of InAs surface and capped QDs. The QDs are grown on a GaAs substrate by MOCVD. By varying growth temperature and buffer layer composition, we achieve surface densities of  $1 \times 10^{11}/\text{cm}^2$ . Photoluminescence spectra from uncapped QDs show an emission wavelength of 1550nm with a FWHM of 140 meV. After overgrowth, the emission wavelength is 1.32  $\mu\text{m}$  with a 40 meV linewidth. All samples are grown on (100) SI-GaAs in a 60 Torr MOCVD reactor. A 2200 Å GaAs layer is grown at 680°C then the temperature is lowered for active region growth. For all samples, the buffer layer thickness (In<sub>0.15</sub>Ga<sub>0.85</sub>As) is 5 MLs followed by 2.5 MLs of InAs. The growth rate and V/III ratio are kept constant at 0.5 ML/s and

52.5, respectively, during QD growth. For capped QDs, growth is interrupted for 60 s after InAs deposition. The QDs are capped with 45 Å In<sub>0.15</sub>Ga<sub>0.85</sub>As then 330 Å GaAs layers. Figures 1(a)-1(f) show AFM images of surface QDs grown on a GaAs (1(a)-1(c)) and an In<sub>0.15</sub>Ga<sub>0.85</sub>As buffer layer (1(d)-1(f)) at temperatures ranging from 460°C to 520°C. Under these conditions, the QDs on GaAs form in a narrow temperature range of 460°C to 485°C. Within this temperature range, the QD formation trends are explained by the increase in surface atom mobility with temperature, i.e. QD size increases as QD density decreases. From AFM scans, we measure an average QD height of 40 Å (45 Å), a density of  $3.5 \times 10^{10}/\text{cm}^2$  ( $1.5 \times 10^{10}/\text{cm}^2$ ) at 460°C (485°C). Outside of this range, QD formation does not occur due to lack of surface mobility at T  $\leq$  460°C and due to In evaporation at T  $\geq$  500°C. The QDs on In<sub>0.15</sub>Ga<sub>0.85</sub>As show a significantly higher dot density due to increased In content and perhaps faster QD nucleation. At T = 485°C, the density is  $8 \times 10^{10} \text{ cm}^{-2}$  with a height of 25 Å. For T > 485°C, the density decreases ( $3.5 \times 10^{10}/\text{cm}^2$ ) as the QD height increases (45 Å) at 520°C. Figure 2 shows RT-PL spectra from the surface QDs grown on 5 MLs of In<sub>0.15</sub>Ga<sub>0.85</sub>As. The peak wavelengths range from 1.46  $\mu\text{m}$  (485°C) to  $\sim$ 1.6  $\mu\text{m}$  (520°C). The FWHM ranges from 160 meV to 120 meV. The peak PL intensity and FWHM decrease with temperature due to the decrease in dot density. The inset of Fig. 2 shows an RT-PL spectrum from capped QDs grown on In<sub>0.15</sub>Ga<sub>0.85</sub>As at 500°C. The PL wavelength is observed at 1.32  $\mu\text{m}$  with a narrow linewidth of 40 meV. The longer wavelength and broader FWHM of surface QDs is partially due to larger and less uniform QDs. The free surface allows the strained InAs atoms to slightly relax which also increases the wavelength. However, the surface electronic barrier provides a deep confinement potential that is essentially the InAs electron affinity ( $\sim$ 5eV). The deep confinement likely contributes a blue-shift to the resulting emission wavelength and increases the separation between energy levels. At 77K, we are not able to excite higher energy levels, even after the ground state has saturated suggesting a single confined state exists for the surface QD. Higher energy levels with separations of 39 meV can be excited in the capped QDs. We will discuss this data and more in our presentation.

#### 9:20 AM

**HH4, Low-Density Strain-Induced InAs Quantum Dots for Triggered Photon Sources:** *Bingyang Zhang*<sup>1</sup>; Matthew Pelton<sup>1</sup>; Zhigang Xie<sup>2</sup>; Glenn Solomon<sup>3</sup>; <sup>1</sup>Stanford University, NTT Basic Rsrch. Labs., Ginzton Lab., Stanford, CA 94035-4085 USA; <sup>2</sup>Stanford University, Solid State Photonics Lab., B113 CISX, Stanford, CA 94305-4075 USA; <sup>3</sup>Stanford University, Solid State Photonics Lab. & Ginzton Lab., 76 S. Ginzton Lab., Stanford, CA 94305-4085 USA

In many areas of physics and engineering which utilize quantum dot (QD) active regions, it is necessary to control the QD size and density. For example, in lasers for telecommunications applications the QD density should be high, while for triggered single photon sources for quantum cryptography it is essential to grow QDs with low density. In this work, the dependence of InAs QD density on the growth temperature has been studied with the goal of achieving low density QD active regions for triggered photon sources. Using molecular-beam epitaxy (MBE), we deposit 1.8 MLs of InAs on GaAs at substrate growth temperatures between 460°C to 525°C. Under these growth conditions, we observe an abrupt change in the QD density. At low growth temperatures island formation is inhibited by poor kinetics. While kinetic barriers are removed as the growth temperature increases, both alloying with the GaAs host and In desorption increase. In this high-temperature region there is a narrow window where large QDs with low density can be made. In this temperature we have found good agreement between our experimental results and theoretical calculations suggesting that thermodynamics indeed plays large role in the QD nucleation and growth. Photoluminescence experiments show that the QD emission wavelength decreases as the substrate growth temperature increases. Since the average QD size increases with substrate growth temperature, one would expect the emission wavelength to correspondingly increase. However, alloying of InAs with the GaAs matrix reduces the emission wavelength at higher growth temperatures, and is responsible for the emission shift to shorter wavelengths. Our efforts are aimed at reducing the QD density for single-photon applications. To this end, low-density InAs QD distributions ( $10 \text{ dots}/\mu\text{m}^2$ ) has been grown using these optimized conditions.

## 9:40 AM Student

### HH5, Excitonic States in Self-Assembled GaN/AlN Quantum Dots:

Vladimir A. Fonoberov<sup>1</sup>; Evghenii P. Pokatilov<sup>1</sup>; Alexander A. Balandin<sup>2</sup>; <sup>1</sup>State University of Moldova, Theor. Physics, Lab. of Multilayer Structure Physics, Chisinau MD-2009 Moldova; <sup>2</sup>University of California–Riverside, Dept. of Electl. Eng., Riverside, CA 92521 USA

GaN-based self-assembled quantum dots (QD) have attracted significant attention owing to their properties, which are different from those of GaAs-based or Ge/Si-based QD structures. Unlike most other III-V compounds, the most common GaN has wurtzite crystal structures. The latter leads to strong built-in piezoelectric field, which affects electronic and optical properties of QDs. Although piezoelectric field effect in planar heterostructures has been for some time a subject of intensive investigation, not much work has been done in studying this effect in quantum dots. In this paper we report results of our detail theoretical study of single particle and exciton states in GaN/AlN QDs. Our model accurately takes into account relevant material parameters of GaN and actual shape of self-assembled quantum dots. Three-dimensional strain field and the built-in electric field inside and outside individual GaN/AlN QDs as well as arrays of coupled QDs are numerically calculated using the elastic continuum approximation. We take into account a difference in the values of the elastic and piezoelectric moduli in GaN dot material and AlN matrix as well as anisotropy of the static dielectric constant. Single particle electron and hole states are found within the strain-dependent eight-band envelope-function model<sup>1</sup>. The electron-hole interaction energy, and self-action potentials are computed for realistic values of the dielectric mismatch at the GaN/AlN interface, which is modeled as a transitional layer. The thickness of the transitional layer is found from experimental data for the GaN-AlN interpenetration depth. Previously reported calculations based on simplified models suggested that due to the built-in electric field, the holes are localized near the bottom of GaN pyramidal-shaped dots while electrons are localized near the top of these truncated pyramids. As a consequence, the electron-hole overlap and, correspondingly, the oscillator strengths of the lowest exciton transition are decreased. On the basis of our model we argue the electron and hole self-action potentials push the carriers inside the dot thus offsetting the above described phenomenon. Thus, the exciton ground state energy differs considerably from the predictions of the simplified models. Using our model we deduce the optical selection rules for the excitonic transitions in GaN/AlN quantum dots. We observed that the oscillator strength is enhanced for transitions between excited states. The latter comes as a result of the increase of the overlap of electron and hole wave functions separated by the built-in field. This is drastically different from GaAs-based and Ge/Si-based quantum dots. <sup>1</sup>V. A. Fonoberov, E. P. Pokatilov, and A. A. Balandin, Phys. Rev. B (in review, 2002).

## 10:00 AM Break

## 10:20 AM

### HH6, The Influence of the Nominal Thickness of InP Quantum Dots on the Surface Morphology and Structural Properties of InAlP Capping Layers:

X. B. Zhang<sup>1</sup>; Jae-Hyun Ryou<sup>1</sup>; Russell D. Dupuis<sup>1</sup>; C. V. Reddy<sup>2</sup>; Venkatesh Narayanamurti<sup>3</sup>; David T. Mathes<sup>3</sup>; Robert Hull<sup>3</sup>; Gabriel Walter<sup>4</sup>; Nick Holonyak, Jr.<sup>4</sup>; <sup>1</sup>The University of Texas at Austin, Microelect. Rsrch. Ctr., Austin, TX 78712 USA; <sup>2</sup>Harvard University, Gordon McKay Lab. of Appl. Sci., Cambridge, MA 02138 USA; <sup>3</sup>The University of Virginia, Dept. of Matls. Sci. & Eng., Charlottesville, VA 22906 USA; <sup>4</sup>The University of Illinois at Urbana–Champaign, Ctr. for Compound Semiconductor Microelect., Urbana, IL 61801 USA

III-Phosphide self-assembled quantum-dot (SAQD or simply QD) structures offer the potential to realize injection lasers operating in the visible spectral region with improved performance characteristics such as low threshold current density, high characteristic temperature, and high differential gain. Also, SAQD growth can overcome the limitation of lattice matching between the substrate and the epitaxial active region due to the intrinsic nature of the growth mode. InP quantum dots have been grown and characterized on direct-bandgap  $\text{In}_{0.49}\text{Ga}_{0.51}\text{P}$  matrices by several research groups and on indirect-bandgap  $\text{In}_{0.49}\text{Al}_{0.51}\text{P}$  and direct-bandgap InAlGaP matrices by these authors. We have recently demonstrated low-threshold injection laser operation of InP quantum dots grown on InAlP and InAlGaP cladding layers. For improved QD lasers, it is important that the overgrown barriers and cladding layers be smooth. In this study, we report the detailed overgrowth characteristics of InP/InAlP and InP/InAlGaP quantum dots (QDs) grown by metalorganic chemical

vapor deposition (MOCVD) on (001) GaAs substrates. The surface morphology, optical, and structural properties were investigated by using atomic force microscopy (AFM), cathodoluminescence (CL), photoluminescence (PL), and X-ray diffraction. AFM images of uncapped QDs as well as CL spectra of capped QDs show that, as expected, the size of InP QDs increases with an increase in nominal InP thickness. For the capped dots, we find that (1) the mode for the growth of the InAlP capping layer has been changed from the step-flow growth mode before to a multilayer growth one after the growth of QDs. This multilayer growth mode results in the formation of mound-like structures on the surface; (2) islands much higher than those mound-like structures were observed on the surface of samples with nominal InP QD thickness above 15 ML; (3) these islands were mostly observed in the valley between the mound-like structures and their density increases with the nominal InP thickness; (4) strong tensile strain was found in the InAlP capping layer after the growth of QDs and the residual strain decreases with the nominal thickness of InP QDs. These data are described in detail and possible origins of these properties are discussed. The impact on the QD PL performance is also presented.

## 10:40 AM Student

### HH7, Ion-Cut-Synthesis of Narrow Gap Nitride Nanostructures:

Xiaojun Weng<sup>1</sup>; W. Ye<sup>1</sup>; S. Clarke<sup>1</sup>; A. Daniel<sup>2</sup>; J. Holt<sup>3</sup>; J. Sipowska<sup>3</sup>; V. Rotberg<sup>4</sup>; R. Clarke<sup>2</sup>; A. Francis<sup>3</sup>; Rachel S. Goldman<sup>1</sup>; <sup>1</sup>University of Michigan, Matls. Sci. & Eng., 2300 Hayward St., Ann Arbor, MI 48109-2136 USA; <sup>2</sup>University of Michigan, Appl. Physics Prog., Ann Arbor, MI 48109 USA; <sup>3</sup>University of Michigan, Dept. of Chem., Ann Arbor, MI 48109 USA; <sup>4</sup>University of Michigan, Nuclear Eng. & Radiological Sci., Cooley Bldg., Ann Arbor, MI 48109 USA

Due to the large size difference between arsenic and nitrogen, mixed anion nitride-arsenide alloys may be grown with emission or detection wavelengths throughout the near infrared range, while maintaining lattice parameters within 1% of common substrates. On the other hand, a consequence of the large N-As size difference is a predicted limited miscibility of (InGa)(AsN) on the anion sublattice, which leads to the formation of phase separation-induced alloy nanostructures. In principle, ion implantation enables the introduction of atoms beyond the solubility limit. In addition, ion-cut, a layer splitting process using ion implantation followed by annealing, has been used for the integration of dissimilar materials. We are exploring a novel method, “ion-cut-synthesis”, in which the synthesis and cleavage of the (InGa)(AsN) layers occur simultaneously. Using a variety of implantation and rapid thermal annealing conditions, we have implanted N ions into both GaAs and InAs. High-resolution transmission electron microscopy (TEM) reveals crystalline nanostructures surrounded by disordered matrices. Electron and X-ray diffraction indicate nanostructure lattice parameters similar to that of cubic GaN. These nanostructures exhibit significant photoluminescence in the near-infrared range, likely due to the incorporation of a small amount of As in GaN. The average nanostructure size increases with annealing temperature while the nanostructure size distribution is self-similar, and the volume fraction remains constant, suggesting a nanostructure coarsening process governed by Ostwald ripening. Interestingly, a layer containing a high density of nanostructures may be cleaved from the substrate by 850°C annealing, providing a new opportunity for the integration of these nanostructures with a variety of substrates. Cross-sectional TEM reveals a series of cavities between the cleaved layer and substrate, suggesting that nitrogen bubbles at the interface provide the cleavage force. We will discuss the mechanisms of layer cleavage, as well as correlations between the optical and structural properties of the nanostructures. This work was supported in part by the DOE (Photovoltaics Beyond the Horizon Program), the Air Force Office of Scientific Research (MURI Program), and the National Science Foundation REU Program.

## 11:00 AM

### HH8, Analysis of Rapid Thermal Annealing of MBE-Grown GaIn(N)As Quantum Wells with GaAs Barriers:

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Rapid thermal annealing is a very useful process to improve the optical properties of nitrogen containing GaAs-based structures. The location of nitrogen in the structure is crucial for determining the optical

properties owing to plasma-related damage introduced during the growth of nitrogen-containing layers. In this talk, we discuss our study of the annealing properties of various structures with 20% In that are annealed at 850°C for 180s. Introducing nitrogen in the barriers instead of in the wells resulted in superior pre-anneal and post-anneal optical properties. The presence of GaAs spacers at the barrier-to-well and well-to-barrier interfaces in the structures with nitrogen in the barriers and no nitrogen in wells, assists in improving both pre-anneal and post-anneal optical properties. The impact of these GaAs spacers as a function of their thickness during annealing will be discussed. It is observed that the optical properties tend to get better with increasing thickness of these spacers. For 1.3 micron emission, quantum wells with >30% indium in the well are required. Structures employing these quantum wells were annealed at various time-temperature combinations ranging from 20 s-100 s and 650°C-950°C. These results will be discussed and compared to the lower In results.

#### 11:20 AM Student

**HH9, Heteroepitaxial ZnO/ZnMgO Quantum Structures in Nanorods:** W. I. Park<sup>1</sup>; S. W. Jung<sup>1</sup>; Y. H. Jun<sup>1</sup>; G. C. Yi<sup>1</sup>; <sup>1</sup>Pohang University of Science and Technology, Matls. Sci. & Eng., San 31, Hyoja Dong, Namku, Pohang 790-784 S. Korea

One-dimensional nanostructures including nanotubes, nanowires and nanorods are potentially ideal functional components for nanometer-scale electronics and optoelectronics. Homogeneous carbon nanotubes and nanowires have already been employed in nanoscale devices. However, heterostructures with well-defined crystalline interfaces are essential for the fabrication of devices on a single wire or a rod, which in principle permit extremely small size and ultrahigh density. Although heterojunctions of carbon nanotubes and nanowires have been developed, heteroepitaxial nanostructures are of particular interest due to their easy and accurate controls for doping and composition in well-defined areas. Remarkable advances in thin film epitaxy have already spurred development of active semiconductor devices with two-dimensional properties. More importantly, controlled heteroepitaxy of ultrathin layers on nanorods make it possible to prepare compositional quantum well nanorods. The quantum well in nanorods introduces a potential perturbing band structure of the host material, confining carriers and yielding a series of narrow subbands. Thanks to these effects, quantum well nanorods add the advantages of tuning a spectral wavelength continuously. Here, we report controlled growth of quantum well nanorods and observation of a blueshift in photoluminescence (PL) spectra of the nanorods. For the fabrications of heterostructures in ZnO nanorods,  $Zn_{1-x}Mg_xO$  ( $x < 0.3$ ) alloy was employed since it has a lattice constant mismatch less than 1% as well as larger fundamental band gap energy than that of ZnO. The quantum well nanorods prepared in this study consist of 10 periods of ZnO/ $Zn_{0.8}Mg_{0.2}O$  superlattices on ZnO nanorods. Structural properties of ZnO/ $Zn_{0.8}Mg_{0.2}O$  quantum well nanorods are investigated using transmission electron microscopy (TEM). Both low magnification and high resolution TEM images exhibited the bright and dark layers in the superlattice, corresponding to ZnO and  $Zn_{0.8}Mg_{0.2}O$  layers, respectively. A quantum confinement effect in the  $ZnO/Zn_{0.8}Mg_{0.2}O$  superlattice nanorods was investigated measuring PL spectra. The PL spectrum of single heterostructure nanorods exhibits the dominant PL emission peak which appears at 3.360 eV presumably results from neutral-donor bound excitons ( $D_0, X$ ) in ZnO. In addition to the dominant PL peak, another weak PL peak was observed at 3.578 eV, ascribed to an excitonic emission from the  $Zn_{0.8}Mg_{0.2}O$  layer in the heterostructure nanorods. However, PL spectra of ZnO/ $Zn_{0.8}Mg_{0.2}O$  MQW nanorods exhibited new emission peaks from 3.478 eV to 3.508 eV depending on well width. The blue shift of the PL peak varied from 118 meV (27 Å) up to 148 meV (12 Å). The systematic increase in PL emission by reducing well width presumably results from the quantum confinement effect.

#### 11:40 AM

**HH10, Self-Assembled Growth of Zinc Oxide Nanoislands and Nanorods by Metalorganic Chemical Vapor Deposition:** Shizuo Fujita<sup>1</sup>; Sang-Woo Kim<sup>2</sup>; Keigou Maejima<sup>2</sup>; Masaya Ueda<sup>2</sup>; Shigeo Fujita<sup>2</sup>; <sup>1</sup>Kyoto University, Intl. Innovation Ctr., Yoshida, Sakyo, Kyoto 606-8501 Japan; <sup>2</sup>Kyoto University, Dept. of Elect. Sci. & Eng., Yoshida, Sakyo, Kyoto 606-8501 Japan

Three-dimensional zinc oxide (ZnO) semiconductor nanostructures are promising for the appearance of unique exciton effects by enhanced confinement of excitons of large binding energy (60meV in bulk ZnO).

This paper describes the successful synthesis of self-organized ZnO nanoislands and nanorods by metalorganic chemical vapor deposition (MOCVD) on Si or sapphire substrates using diethylzinc (DEZn) and nitrous oxide ( $N_2O$ ) as source precursors. The ZnO nanoislands were fabricated on 25-nm thick  $SiO_2$  layers formed by thermal oxidation of Si (111) substrates. Formation of nanoislands was confirmed by atomic force microscopy under the growth temperature between 400 and 500°C. Considering the low adhesion probability of ZnO in MOCVD on  $SiO_2$ , which has been generally observed in our previous research, it is expected that accidental nucleation of ZnO molecules is followed by adsorption of adatoms migrating on the  $SiO_2$  surface and growth of ZnO islands. In this sense, the growth mechanism of the ZnO islands is supposed to be the Volmer-Weber type. As the growth temperature increases, the island size decreases and the island density increases, and at the growth temperature of 500°C, the width and height of islands were approximately 35nm and 10nm, respectively, with the density of  $6 \times 10^9 \text{cm}^{-2}$ . On the other hand, at the growth temperature of higher than 550°C, the formation of nanoislands was hardly seen probably due to enhanced evaporation of adatoms. Efforts to increase the island density and to characterize the optical properties are now going on. The ZnO nanorods were fabricated on sapphire (11-20) substrate also at the growth temperature of 400-500°C. The reason for using the (11-20) substrates is to suppress the formation of rotational domains compared to (0001) substrates<sup>1</sup>. As expected, the nanorods were c-axis oriented with the relationship of ZnO(11-20)//sapphire(0001), i.e., no rotational domain is clearly observed. The diameter (10-50nm), height (30-600nm), and density ( $2 \times 10^{10}$ - $2 \times 10^{11} \text{cm}^{-2}$ ) could be controlled by the growth conditions. The diameter seems to be smaller compared to the nanowires ever fabricated on sapphire (0001) substrates and contributed to nanolasers<sup>2</sup>. Photoluminescence spectra from the nanorods tended to be blue-shifted with tailing to short wavelength compared to ZnO bulk or thin film standard samples. Since the preliminary calculation suggests the energy-shift of 50meV for nanorods of 10-nm diameter, the present results may be associated with quantum size effects shifting the emission spectra toward shorter wavelengths according to the size of nanorods. Research is now directing toward precise control of size and density, including their distribution, for developing new and novel optical functions supported by confined excitons. <sup>1</sup>P. Fons et al., J. Cryst. Growth 209, 532 (2000), <sup>2</sup>M. H. Huang et al., Science 292, 1897 (2001).

## Session II: Silicon Carbide: Defects

Friday AM Room: Corwin East  
June 28, 2002 Location: University of California

*Session Chair:* Michael Capano, Purdue University, Sch. of Elect. & Compu. Eng., 1285 EE Bldg., W. Lafayette, IN 47907-1285 USA

#### 8:20 AM

**III, Doping and Temperature Effects on Strain in N-Type 4H-SiC Epilayers:** Robert S. Okojie<sup>1</sup>; Ming Zhang<sup>2</sup>; Pirouz Pirouz<sup>2</sup>; Leonard J. Brillson<sup>3</sup>; Sergey Tumakha<sup>3</sup>; Gregg Jessen<sup>3</sup>; <sup>1</sup>NASA Glenn Research Center, Sensors & Elect. Branch, 21000 Brookpark Rd., Cleveland, OH 44135 USA; <sup>2</sup>Case Western Reserve University, Matls. Sci. Eng., Cleveland, OH 44106 USA; <sup>3</sup>Ohio State University, Electl. Eng., 205 Drees Lab., Columbus, OH 43210 USA

In this current work on Temperature-Induced Stacking Fault (TI-SF) formation, we focused on the role of doping and temperature in inducing lattice mismatch and generating stacking faults. High-resolution X-ray diffraction (HRXRD) and cross section transmission electron microscopy (XTEM) was used to investigate the intrinsic strain in three nitrogen doped 4H-SiC epilayers grown homoepitaxially on high resistivity p-type 4H-SiC substrates. The effect of thermal treatment on lattice mismatch for different doping levels was also investigated with the same analytical techniques. A direct correlation was found between epilayer strain, TI-SF density, doping, and temperature. We have measured the strain in n-type 4H-SiC epilayers as function of nitrogen doping after

epilayer growth. Also measured was the residual strain at room temperature after annealing the samples at selected temperatures and times between 800°C and 1400°C. The annealing of each sample was performed at only one temperature and then cooled down and the lattice mismatch was measured by HRXRD. The intrinsic strain after epilayer growth increased from  $0.525 \times 10^{-3}$  for a sample with doping of  $4.1 \times 10^{17} \text{ cm}^{-3}$  to  $1.6 \times 10^{-3}$  for a sample doped at  $1.7 \times 10^{19} \text{ cm}^{-3}$ . For the lowest doped samples, the measured strain in the epilayer was practically invariant after annealing up to 1150°C and cooling. In the case of the medium doped samples, the measured strain upon cooling from 1150°C decreased slightly. In contrast, measured strain in the highest doped samples showed a rapid decrease upon cooling from anneal temperatures between 800°C and 1150°C. After annealing at 1400°C and subsequent cooling down, the measured strain in samples of the highest and lowest doping levels increased slightly, while the medium doped sample exhibited only a small decrease. Strain conditions at this high temperature (1400°C) could be attributed to relaxation as the temperature approached that of epilayer growth regime. The doping-induced strain in the epilayer is attributed to the smaller atomic radius of nitrogen preferentially substituting for carbon, which has a relatively larger atomic radius. The decrease in strain with doping level after cooling from between 800°C-1150°C suggests a relief mechanism via activation of mobile Shockley partials, resulting in high density of stacking faults found only in the highest doped epilayer. Fig. 2 shows the XTEM of stacking faults in the highest doped epilayer ( $1.7 \times 10^{19} \text{ cm}^{-3}$ ). No stacking faults were observed in the lower doped samples investigated. To our knowledge, this is the first experimental measurement of strain values attributed to different nitrogen doping concentrations and temperature induced lattice mismatch. This work suggests that a maximum doping level exists for the process fabrication and operation of reliable devices.

**8:40 AM**

**II2, Stacking Fault Nucleation and Growth in SiC PiN Diodes:** *Robert Stahlbush*<sup>1</sup>; Mark Twigg<sup>2</sup>; Mohammad Fatemi<sup>3</sup>; Jesse Tucker<sup>4</sup>; Jeffrey Fedison<sup>4</sup>; Steve Arthur<sup>4</sup>; Shaoping Wang<sup>5</sup>; <sup>1</sup>Naval Research Laboratory, Code 6813, 4555 Overlook Ave. SW, Washington, DC 20375 USA; <sup>2</sup>Naval Research Laboratory, Code 6812, 4555 Overlook Ave., SW, Washington, DC 20375-5320 USA; <sup>3</sup>Naval Research Laboratory, Code 6861, 4555 Overlook Ave. SW, Washington, DC 20375 USA; <sup>4</sup>General Electric, CRD, Niskayuna, NY 12309 USA; <sup>5</sup>Sterling Semiconductor, SC, Danbury, CT 12345 USA

SiC power devices have the potential to vastly outperform Si power devices. In addition to the increase in performance afforded by the larger bandgap and higher breakdown voltage of SiC, SiC devices are expected to exhibit higher tolerance to extreme ambient conditions. However, there are reliability problems due to material defects. Recently, long-term reliability tests of 4H-SiC PiN diodes have indicated that bipolar devices exhibit increased forward on-state voltage with stress under constant forward current and the degradation has been attributed to stacking fault formation. This presentation focuses on the nucleation and growth of stacking faults during the forward-biased operation of 4H SiC PiN diodes from several wafers studied by light emission imaging. The p+ anodes were formed by ion implantation at 650°C of B/Al/C and were activated by annealing at 1700°C in Ar using a SiC wafer as a cap. The mask design includes diodes with a grid of openings in the p-contact metal layers over the anode for observing light emission. Stacking fault growth has been investigated at current densities of 80 and 160 A/cm<sup>2</sup>. In the diodes that we have studied to date, the stacking faults are first observed 1-2 μm below the surface. Many of the stacking faults appear within tens of seconds of stressing although we have observed stacking faults that started growing after more than an hour of stressing. The stacking faults grow along the basal plane, which is tilted 8° with respect to the wafer surface. The growth patterns can be quite complicated and reflect the non-uniform stress within the epi layer. All of the stacking faults expand to (or near to) the SiC surface. Many of them grow within the epi layer until they span the active region of the diode. The growth of others is pinned—either “permanently” or temporarily. We are studying the growth at both lower and higher current densities. At lower densities, the initial formation of the stacking faults can be examined in more detail, and higher densities may force previously pinned stacking faults to start growing again.

**9:00 AM**

**II3, Correlation of Bipolar Degradation and Mechanical Stress in 4H-SiC PiN Diodes:** *Jesse B. Tucker*<sup>1</sup>; Jeffrey B. Fedison<sup>1</sup>; Stephen D. Arthur<sup>1</sup>; Larry B. Rowland<sup>1</sup>; James W. Kretschmer<sup>1</sup>; <sup>1</sup>General Electric Global Research Center, Semiconductor Tech. Prog., One Research Cir., Niskayuna, NY 12309 USA

Stacking fault propagation has been identified as a source of permanent increase in the forward voltage drop during long-term forward conduction of SiC PiN diodes. The source of these stacking faults needs to be identified and eliminated in order to overcome the effects of bipolar degradation. Recent data has shown that a correlation exists between the degree of forward voltage increase and the severity of mechanical stress in the wafer. Cross-polarizer images of the starting wafer show regions of uniform intensity and region of disorder where disordered regions are attributable to mechanical stress in the wafer. The diodes investigated in this study were made on 35mm 4H-SiC starting material with lightly doped n-type epitaxial layers of 10 to 12mm thick. A p+ anode, three-zone p-type junction termination extension (JTE), and n+ field stop were implanted sequentially giving a planar device structure. The anode area is  $6.3 \times 10^{-3} \text{ cm}^2$ . Electrical measurements of the diodes show a nominal forward drop of 3.8 V at 0.5 A forward bias. The devices achieved blocking voltages of above 1100V with nominal leakage currents of 100 pA. Automated electrical testing was performed on the fabricated diodes where the devices were held at a forward bias of 1A and forward current-voltage sweeps were taken at periodic intervals over a period of 30 minutes. The forward voltage drop was then mapped for all diodes on the wafer. Comparison of the electrical data with the optical cross-polarizer data indicates a strong correlation between regions that are optically uniform having little or no forward voltage degradation. Conversely, regions having high forward voltage degradation can be seen to be optically disordered. These results strongly suggest the influence of mechanical stress in the wafer on the forward voltage drop increase of electrically stressed diodes. The results will be further confirmed by X-ray topography. A similar test will be performed on Schottky diodes to determine the effect of wafer stress (if any) on the performance of unipolar Schottky diodes.

**9:20 AM**

**II4, Extended Defects Formed During the Forward Bias of 4H SiC PiN Diodes:** *Mark E. Twigg*<sup>1</sup>; Robert E. Stahlbush<sup>1</sup>; Mohammad Fatemi<sup>1</sup>; S. D. Arthur<sup>2</sup>; J. B. Fedison<sup>2</sup>; J. E. Tucker<sup>2</sup>; S. Wang<sup>3</sup>; <sup>1</sup>Naval Research Laboratory, Elect. Sci. & Tech. Div., Code 6812, Washington, DC 20375-5320 USA; <sup>2</sup>General Electric Corporate Research and Development Center, Elect. Devices, One Research Cir., Niskayuna, NY 12309 USA; <sup>3</sup>Sterling Semiconductor, Crystal Growth, 310 Argent Dr., Danbury, CT 13011 USA

Light emission imaging (LEI) reveals that the degradation of 4H SiC PiN diodes under forward voltage operation is due to the evolution of extended defects and the migration of these defects to the surface of the active device region. Plan-view transmission electron microscopy (TEM), of diodes that have been biased at ambient-temperature during LEI observation, identifies these extended defects as stacking faults and narrowly-dissociated dislocations. By comparing *ex situ* TEM observations with the results of *in situ* LEI experiments, we are able to identify the extended defects formed during device operation. This comparison between TEM and LEI observations also allows the origin of these defects to be determined, an important step in the ultimate elimination of these defects. Furthermore, the results of these experiments suggest that a different mechanism is responsible for plastic flow in 4H SiC in biased PiN diodes, than for 4H SiC subjected to strain alone. Angle lapping using a tripod polisher and diamond abrasive films have been used to prepare plan-view TEM samples with an electron-transparent region that is 1mm wide and tens of microns in from the sample edge. A chemical etch was used to remove the oxide and metallization layers to prevent them from occluding the TEM image. Argon ion milling was used to remove residual contamination and metallization. The motion of dislocations and stacking faults are strain-driven, as suggested by *in situ* LEI observations recorded during device operation. TEM observation of extended stacking faults penetrating the surface of the device, after sustained operation, suggests the displacement of Shockley partial dislocations. Our TEM observations also indicate that narrowly-dissociated dislocations occur more frequently than stacking faults after sustained device operation. Plastic deformation tests reported by Pirouz et al. indicate that the motion of narrowly-dissociated dislocations only occur during



plastic flow at temperatures above the ductile-to-brittle transition temperature (~1100°C); below this temperature plastic flow is dominated by leading Shockley partial dislocations bounding stacking faults. The possibility that narrowly-dissociated dislocations may occur during device operation at ambient temperature may be attributed to carrier recombination channeling energy into extended defects. Future work will include cross-sectional TEM of samples prepared by focused ion beam (FIB) milling, in order to determine the origin of these extended defects.

#### 9:40 AM Student

**I15, Spontaneous Formation of Stacking Faults in Highly Doped 4H-SiC Wafers During Annealing:** *Thomas Kuhr*<sup>1</sup>; Jinqiang Liu<sup>1</sup>; Hun J. Chung<sup>1</sup>; Frank Szmulowicz<sup>2</sup>; Marek Skowronski<sup>1</sup>; <sup>1</sup>Carnegie Mellon University, Matls. Sci. & Eng., 5000 Forbes Ave., Pittsburgh, PA 15213 USA; <sup>2</sup>University of Dayton Research Institute, Metals & Ceram. Div., Dayton, OH 45469 USA

Recent results have shown that highly doped 4H-SiC will structurally transform to 3C if subjected to processing conditions associated with oxidation and contact annealing. In addition, stacking faults leading to device degradation have been shown to form during forward bias testing of pin diode structures at room temperature. Several mechanisms have been proposed to explain the transformations, including point defect coalescence, stress due to doping differences between substrate and epilayer, and quantum well action. In this work, 4H-SiC samples doped with nitrogen at  $\sim 3 \times 10^{19} \text{ cm}^{-3}$  were annealed in Ar for 90 min at 1150°C. Transmission electron microscopy revealed stacking faults at a density of  $\sim 70 \text{ mm}^{-1}$  while faults were not found to exist prior to annealing. All faults examined were double layer Shockley faults formed by shear on two neighboring basal planes. The structural transformation was interpreted as due to quantum well action, a mechanism where electrons in highly n-type 4H-SiC enter stacking fault-induced quantum well states to lower the system energy. The net energy gain was calculated as a function of temperature and nitrogen doping concentration through solution of the charge neutrality equation. At low temperatures and high nitrogen doping concentrations, the energy gain is significantly greater than the energy required to increase the area of either single or double layer Shockley faults. At high temperatures ( $>1575^\circ\text{C}$  for  $1 \times 10^{19} \text{ cm}^{-3}$ ) the Fermi level is below the fault energy level, stacking fault states are not preferentially populated, and this mechanism is not expected to be active. At intermediate temperatures (700 to 1575°C), crystals with high doping levels are expected to spontaneously form double layer stacking faults in agreement with our observations. Single layer stacking faults are not expected to form at 1150°C for nitrogen doping concentrations below  $1 \times 10^{20} \text{ cm}^{-3}$ , and double layer faults are expected to form at concentrations greater than  $3 \times 10^{18} \text{ cm}^{-3}$ . Remarkable agreement between the model and empirical data indicates that quantum well action is likely the dominant fault formation mechanism at device processing temperatures.

#### 10:00 AM Break

#### 10:20 AM

**I16, Processing-Induced Polytype Transformation in Heavily N-Doped 4H-SiC:** *Brian J. Skromme*<sup>1</sup>; Krishna Palle<sup>1</sup>; Light R. Bryant<sup>1</sup>; Hira Meidia<sup>2</sup>; Subhash Mahajan<sup>2</sup>; Christian D. Poweleit<sup>3</sup>; William M. Vetter<sup>4</sup>; Michael Dudley<sup>4</sup>; Karen Moore<sup>5</sup>; Ted Gehoski<sup>5</sup>; <sup>1</sup>Arizona State University, Dept. of Electl. Eng. & Ctr. for Solid State Elect. Rsrch., PO Box 875706, Tempe, AZ 85287-5706 USA; <sup>2</sup>Arizona State University, Cheml., Bio., & Matls. Eng., PO Box 876006, Tempe, AZ 85287 USA; <sup>3</sup>Arizona State University, Dept. of Physics & Astron., PO Box 871504, Tempe, AZ 85287 USA; <sup>4</sup>State University of New York at Stony Brook, Dept. of Matls. Sci. & Eng., Stony Brook, NY 11794-2275 USA; <sup>5</sup>Motorola, Inc., Physl. Scis. Rsrch. Lab., 7700 S. River Pkwy., Tempe, AZ 85284 USA

In applications of 4H-SiC to power devices such as rectifiers, heavy substrate doping is desirable to minimize series resistance. Here we describe a pronounced crystalline instability in this material, which can arise if the substrate doping is increased above a critical threshold. Commercial wafers with N doping levels around  $3 \times 10^{19} \text{ cm}^{-3}$  (0.008 ohm-cm resistivity) and moderately-doped ( $1\text{-}1.5 \times 10^{17} \text{ cm}^{-3}$ ), 2  $\mu\text{m}$  thick epilayers are shown to undergo pronounced surface distortions in their most heavily doped (central) portions when subjected to thermal oxidation at 1150°C for 90 min. in dry O<sub>2</sub>. The initially smooth surfaces display pronounced  $\sim 2 \mu\text{m}$  high ridges and dimpling immediately after oxidation. Similar effects are never observed for similar structures on more lightly-doped substrates ( $n < 1.1 \times 10^{19} \text{ cm}^{-3}$ ). Synchrotron-based white beam X-ray to-

pography reveals a dense network of dislocations in the central regions of the wafers after oxidation, along with distortion of the wafers due to strain. Schottky diodes were fabricated on several such wafers using Ti, Ni, or Pt metallization. Current-voltage and capacitance-voltage measurements reveal a uniform, metal work function-independent reduction of 0.47 V in barrier height in the distorted regions. This result suggests an increase in the electron affinity of the semiconductor near its surface, possibly due to a cubic polytype. Room and low temperature photoluminescence measurements show a replacement of the normal 4H band-edge peaks by new lines just above the band gap of 3C-SiC in the distorted regions (e.g., from 2.405-2.53 eV at 1.7K). On the other hand, Raman scattering and X-ray topography do not detect a cubic phase. The seemingly contradictory measurements are largely reconciled by cross-sectional transmission electron microscopy data showing thin lamellae of cubic material due to stacking faults in a predominantly 4H-SiC matrix. Further work is in progress to establish the precise cause and detailed nature of the transformations we have observed. This work was supported by the National Science Foundation under Grant No. ECS-0080719.

#### 10:40 AM Student

**I17, Evidence of Dislocation Nucleation During Homo-Epitaxy of 4H Silicon Carbide:** *Seoyong Ha*<sup>1</sup>; Marek Skowronski<sup>1</sup>; <sup>1</sup>Carnegie Mellon University, Matls. Sci. & Eng., 5000 Forbes Ave., Pittsburgh, PA 15213 USA

Atomic force microscopy, transmission electron microscopy (TEM) and optical microscopy were applied to study the dislocations in homo-epitaxial layers grown on 4H silicon carbide (SiC) substrates. It is generally accepted in homo-epitaxial growth that dislocations in epilayers are inherited from the substrates and no new dislocations are nucleated. The results presented below indicate that there are new dislocations formed during homo-epitaxy of SiC. The samples examined in this study were off-oriented 4H-SiC wafers with 10  $\mu\text{m}$  thick epitaxial layers grown by chemical vapor deposition techniques at low pressure. The layers were low-doped ( $10^{15}\text{-}10^{16} \text{ cm}^{-3}$ ) n-type grown on n<sup>+</sup> substrates with carrier density of about  $10^{18} \text{ cm}^{-3}$ . As-grown epilayers were etched in molten KOH to reveal the locations where dislocations intersect the (0001) Si surface. Characteristic arrays of etch pits oriented in the direction perpendicular to the off-cut and parallel to the growth steps were observed on the wafer surface. The arrays did not originate from the substrate but nucleated during epitaxy as demonstrated in the experiment consisting of gradual polishing and re-etching of the epilayer/substrate structure. The nucleated dislocation arrays consisted of pairs of threading dislocations indicating a loop structure. Each array was a single line with a length between 30 and 600  $\mu\text{m}$ . The linear density of pairs in an array was about  $1 \times 10^3 \text{ cm}^{-1}$ . The distance between pairs was between 2 and 10  $\mu\text{m}$ , twice to three times longer than the distance between dislocations in a pair. The line connecting two dislocations in a pair was parallel for all pairs in an array, but formed different angles with the off-cut direction for different arrays. Etching study showed that each array nucleated at once, but the nucleation of arrays occurred uniformly throughout the growth. The dislocation distribution was confirmed by TEM. The Burgers vectors of dislocations in a pair were parallel to each other, which is consistent with the interpretation of a pair as two threading segments of a loop. In some epilayers, the density of dislocations nucleated in this manner exceeded  $10^4 \text{ cm}^{-2}$ . Possible nucleation mechanisms will be discussed.

#### 11:00 AM

**I18, Charge Exchange Among Defects During High Temperature Annealing of 4H High Purity SiC:** *David Alvarez*<sup>1</sup>; Mary Ellen Zvanut<sup>1</sup>; Valeriy Kononov<sup>1</sup>; <sup>1</sup>University of Alabama at Birmingham, Physics Dept., Birmingham, AL 35294 USA

Understanding the role of electrically active point defects is important for developing SiC substrates for electronic applications. Our work presents studies of high purity 4H SiC in which we see defects that anneal between 1000°C and 1600°C and may be altering the Fermi level by transferring charge to other defects. High purity SiC samples were heat-treated in flowing 99.999% pure Ar at temperatures ranging from 600°C to 1600°C. The duration of the set temperature was ½ hour for each anneal. Samples were then studied using X-band electron paramagnetic resonance (EPR) between 4K and 300K. Our EPR data were recorded in derivative mode, and the total number of centers was counted by double integration of the spectra and comparison to a standard. Analysis at 77K of the data before annealing and after 1100°C and 1500°C anneals indicate a broad,  $\sim 15 \text{ G}$  FWHM, featureless signal superimposed on a sharper, more thermally stable line. The concentration of the defect represented



by the broad line begins to decrease at temperatures as low as 600°C. The broad line-width and low anneal temperature suggest that the 15G wide spectrum represents  $\sim 10^{13}$  randomly oriented dangling bonds found at or near the surface. After the amplitude of the broad line is reduced, at least three signals with total concentration  $\sim 10^{14}$  cm<sup>-3</sup> are apparent. One sharp line is attributed to a carbon vacancy. EPR measurements at 4K indicate a multi-line pattern due to the shallow boron acceptor. A signal seen at 3476 G has not yet been identified with a specific defect structure. Comparison of spectra taken after the 1000° and 1500°C anneals suggests that reducing the concentration of this unidentified center releases an electron or hole that is subsequently transferred to the carbon vacancy and/or boron acceptor creating additional paramagnetic states of these centers. Spectra obtained after the 1600°C anneal indicate that the charge transfer continues, although the involvement of the line at 3476G is no longer apparent. Such a rearrangement of charge may shift the Fermi level and possibly change the response of a SiC device.

#### 11:20 AM

**II9, Defect Engineering in SiC: Hydrogen Interaction with Defects and Impurities:** *Yaroslav Koshka*<sup>1</sup>; Janna B. Dufrene<sup>2</sup>; Jeffrey B. Casady<sup>1</sup>; <sup>1</sup>Mississippi State University, Elect. & Compu. Eng., PO Box 9571, Mississippi State, MS 39762 USA; <sup>2</sup>SimiSouth Laboratories, Inc., 1 Research Blvd., Starkville, MS 39762 USA

In this work, we investigate the influence of a thermal budget inherent to SiC device processing on the ability to keep hydrogen passivating desirable trapping centers after different processing steps. Competing mechanisms for hydrogen trapping and release by two different kinds of trapping centers—Al acceptors (Al-H complex) and complex involving Si vacancy ( $V_{Si}+H$ )—during hydrogenation as well as during different annealing steps were observed. Aluminum-doped SiC epitaxial layers grown by APCVD were used for the experiment. Hydrogen was incorporated during etching the epilayers in inductively coupled plasma etching (ICP) system using a CHF<sub>3</sub> etch as well as by plasma hydrogenation in the ICP system. Hydrogen incorporation in the material and formation of hydrogen complexes was monitored using PL spectroscopy. Hydrogen penetration was also confirmed by SIMS. Relatively low temperatures at the sample surface during etching and during hydrogenation (estimated to be below 400-450°C) enabled rather efficient trapping of the hydrogen incorporated in the material by Al acceptors. Amount of hydrogen trapped into the  $V_{Si}+H$  complex showed a strong dependence on the concentration of Al acceptors. PL intensity of the  $V_{Si}+H$  complex after hydrogenation was observed to be the strongest for samples lightly doped with Al and decreased for higher doped samples. Both the position of the Fermi level and the competing process of hydrogen trapping by Al acceptors could be responsible for the less efficient formation of the  $V_{Si}+H$  complex in the higher doped epilayers. Annealing of hydrogenated SiC epilayers at temperatures above 500°C in nitrogen caused an essential redistribution of hydrogen between the two trapping centers. Annealing at 500 to 700°C that is known to be sufficient for dissociation of Al-H complex produced partial to complete recovery of Al bound exciton PL depending on the annealing time. However, hydrogen that had been released from Al acceptors did not outdiffuse from the epilayers at these moderate temperatures but got trapped in the  $V_{Si}+H$  complex, which was observed as a strong increase of the  $V_{Si}+H$  photoluminescence. Sufficiently long annealing produced complete migration of hydrogen from Al traps to traps at Si vacancy. Consequently, trapping center at Si vacancy was identified as an efficient “storage” of hydrogen up to temperatures of about 700°C or even higher for relatively short processing times. Sufficiently long annealing at higher temperatures above 900°C caused dissociation of the  $V_{Si}+H$  complex, which resulted in a complete hydrogen outdiffusion from the epilayers. More detailed information on the threshold conditions for the de-trapping of hydrogen from the trap at Si vacancy as well as conditions to provide a reverse migration of hydrogen from the “storage” at Si vacancy to Al acceptors for acceptor re-passivation will be reported.

#### 11:40 AM

**II10, Late News**

## Session JJ: Wide Bandgap Substrates and Surfaces

Friday PM  
June 28, 2002

Room: Lotte Lehmann  
Location: University of California

*Session Chairs:* Laura Rea, US Air Force, WL/MLPO, 3005 P St., Ste. 6, WPAFB, OH 45433-7707 USA; Alan Doolittle, Georgia Institute of Technology, Sch. of Elect. & Compu. Eng., 777 Atlantic Dr., Atlanta, GA 30332-0250 USA

#### 1:20 PM

**JJ1, Growth of GaN on Electrical Conductive ZrB<sub>2</sub> Substrate by Molecular Beam Epitaxy:** *Jun Suda*<sup>1</sup>; Hiroyuki Matsunami<sup>1</sup>; <sup>1</sup>Kyoto University, Dept. of Elect. Sci. & Eng., Yoshida Honmachi, Sakyo-ku, Kyoto 6068501 Japan

Electrically conductive substrates are desirable for group-III nitride devices with a vertical current flow, such as light-emitting devices and power switching devices. In this paper, epitaxial growth of GaN on an electrically conductive metal boride substrate is presented. Zirconium diboride (ZrB<sub>2</sub>) is a semi-metal compound (several  $\mu$ -cm) with a good thermal conductivity (comparable to Si). This compound has a hexagonal AlB<sub>2</sub>-type crystal structure. The a-axis lattice constant is 3.169 Å, which is almost lattice-matched to GaN (3.188 Å) and perfectly lattice-matched to Al<sub>0.25</sub>Ga<sub>0.75</sub>N. High-speed bulk growth of ZrB<sub>2</sub> using a floating zone method has been developed,<sup>1,2</sup> which makes possible to utilize this compound as a substrate. Development of high-quality epitaxial growth on the substrate is one of key issues. GaN was grown on a mirror-polished ZrB<sub>2</sub> (0001) substrate by molecular beam epitaxy (MBE) using elemental Ga and radio frequency (RF) plasma-excited active nitrogen. After a thermal cleaning in an ultrahigh vacuum, direct growth of GaN was carried out. Epitaxial growth was confirmed by *in situ* reflection high-energy electron diffraction (RHEED) observation and X-ray diffraction (XRD) pole-figure measurement. The epitaxial relationship was  $[0001]_{\text{GaN}} // [0001]_{\text{ZrB}_2}$  and  $[1-100]_{\text{GaN}} // [1-100]_{\text{ZrB}_2}$ . No in-plane rotation was observed. A RHEED pattern was spotty just after the start of growth, indicating three-dimensional nucleation of GaN on the ZrB<sub>2</sub> substrate. The spotty pattern was unchanged all through the growth. The surface morphology of the GaN layer was very rough. Low-temperature (16K) photoluminescence (PL) was very weak and dominated by defect- and cubic phase-related emissions. These results suggest that nucleation control is a key to realize high-quality GaN growth. The effect of low-temperature (LT)-grown GaN buffer layer was investigated. GaN was grown at 400-500°C. An intense streak pattern of RHEED was clearly observed after 1-min growth of buffer layer ( $\sim 10$  nm), indicating that flat crystalline GaN was successfully formed on the substrate. A 1  $\mu$ m-thick GaN layer was grown on the buffer layer at an elevated temperature. The PL spectrum of the GaN layer was dominated only by excitonic emission. Other properties (XRD, roughness) were also improved. <sup>1</sup>S. Otani and H. Kinoshita, Abst. of 13th Int. Conf. of Crystal Growth, Kyoto (Aug., 2001); <sup>2</sup>H. Kinoshita, S. Otani, S. Kamiyama, H. Amano, I. Akasaki, J. Suda and H. Matsunami, Jpn. J. Appl. Phys. 40 (2001) L1280-L1282.

#### 1:40 PM

**JJ2, Properties of Bulk GaN Crystals Grown at High Pressure and High Temperature:** *Mark P. D'Evryn*<sup>1</sup>; Dong-Sil Park<sup>1</sup>; Kristi J. Narang<sup>1</sup>; Steven F. Leboeuf<sup>2</sup>; <sup>1</sup>GE Global Research Center, Ceram. Proc. Lab., PO Box 8, Schenectady, NY 12301 USA; <sup>2</sup>GE Global Research Center, Wide-Bandgap Semiconductor Lab., PO Box 8, Schenectady, NY 12301 USA

The performance of many GaN-based optoelectronic and electronic devices is currently limited by the presence of threading dislocations and other defects originating from lattice- and thermal-expansion-mismatched substrates such as sapphire and silicon carbide. The optimum solution is of course to use high quality bulk GaN as a substrate. Many groups worldwide are developing technology for quasi-bulk substrates, in which a thick GaN film is deposited onto a sacrificial substrate by vapor phase transport and then removed. However, such methods intrinsically lead to higher defect concentrations and costs relative to wafers sliced from bulk-grown boules. We have grown GaN crystals by temperature-gradi-

ent recrystallization at high pressure and high temperature, using apparatus and techniques adapted from those used to synthesize diamond. Our largest crystals to date are several mm in diameter but we believe the method can be scaled up to at least 50mm. The crystals are transparent, well faceted and appear to have low dislocation densities, exhibiting highly uniform cathodoluminescence.

## 2:00 PM

### JJ3, Optical Properties of Bulk GaN Crystals Grown from a Na-Ga Melt:

*Brian J. Skromme*<sup>1</sup>; Krishna Palle<sup>1</sup>; Christian D. Poweleit<sup>2</sup>; Hisanori Yamane<sup>3</sup>; Francis J. Disalvo<sup>4</sup>; <sup>1</sup>Arizona State University, Dept. of Electl. Eng. & Ctr. for Solid State Elect. Rsrch., PO Box 875706, Tempe, AZ 85287-5706 USA; <sup>2</sup>Arizona State University, Dept. of Physics & Astron., PO Box 871504, Tempe, AZ 85287-1504 USA; <sup>3</sup>Tohoku University, Inst. for Adv. Matls. Proc., Sendai 980-8577 Japan; <sup>4</sup>Cornell University, Dept. of Chem., 102 Baker Lab., Ithaca, NY 14853 USA

Current nitride semiconductor technology is almost exclusively based on heteroepitaxy on lattice and thermally mismatched materials such as sapphire or SiC. Development of true bulk substrates could lead to substantially reduced defect density and improved material properties. Growth from Na-Ga melts in N<sub>2</sub> overpressures has recently produced crystals as large as 5mm in size. Here, we describe detailed optical characterization of wurtzite GaN grown by this method using low and room temperature photoluminescence (PL), reflectance, and micro-Raman scattering. Growth was typically performed at 750-800°C under 5 MPa of N<sub>2</sub> in BN crucibles for 200-300 h. The Na fraction in the melt varied from 0.60 (yielding prismatic crystals) to 0.67 (yielding platelets). The resulting crystals are transparent and colorless and up to several mm in size. Three typical morphologies obtained under the various growth conditions were studied, including small (~mm or less) prismatic crystals; small thin platelets (mm or less) with typically rough, stepped surfaces on one side (and smoother surfaces on the opposite side); and larger (several mm), thicker platelets. PL spectra show marked correlations with habit and growth conditions. Larger platelets show a dominant neutral donor-bound exciton (D<sup>0</sup>,X) peak with 2.2 meV FWHM at 1.7K, with a weak residual Mg or Si acceptor peak. In contrast, the smaller, stepped platelets show an additional strong structure around 3.411 eV, which is generally assigned to excitons bound to structural defects. These samples also show a strong residual Zn acceptor peak around 2.9 eV, which is sometimes much stronger on the rougher (N polar) side than on the smoother (Ga polar) faces, implying polarity-dependent incorporation. Prismatic samples generally lack the 3.41 eV PL and show sharp (D<sup>0</sup>,X) peaks. Yellow PL related to Ga vacancies (around 2.2 eV) is virtually absent in all samples, which may be due to the Ga-rich melt during growth. Small platelets grown in purer pBN crucibles with purified (99.95%) Na show highly structured excitonic emission at 1.7K, with exceptionally strong peaks as narrow as 0.2 meV FWHM. We report the first observation of a triplet for the Zn acceptor-bound exciton at 3.4542, 3.4546, and 3.4556 eV, which shows anomalous thermalization. Two-electron satellites of the (D<sup>0</sup>,X) peaks are observed involving  $n=2$  and  $n=3$  states of a 33.6 meV residual donor tentatively assigned to O<sub>N</sub>. Fine structure on the principal (D<sup>0</sup>,X) peaks and four peaks assigned to free and bound  $n=2$  A free excitons are observed. Raman spectra of the small platelet samples show a pronounced A<sub>1</sub>(LO) peak at 733 cm<sup>-1</sup>, virtually unshifted by plasmon interactions. This observation implies free carrier concentrations less than a few x 10<sup>16</sup> cm<sup>-3</sup>, which may be due to scavenging of impurities by Na in the melt. The largest platelet shows a slight shift and weakening of the mode, implying carrier concentrations at most 2-3 x 10<sup>17</sup> cm<sup>-3</sup>. The purity and crystal quality implied by these observations is unique to date for bulk GaN. This work was supported by the Office of Naval Research (C. E.C. Wood) under MURI contract N00014-01-1-0716.

## 2:20 PM

**JJ4, High Purity Semi-Insulating 4H-SiC Substrates for Microwave Device Applications:** *J. R. Jenny*<sup>1</sup>; D. P. Malta<sup>1</sup>; St. G. Müller<sup>1</sup>; A. P. Powell<sup>1</sup>; V. F. Tsvetkov<sup>1</sup>; H. M. Hobgood<sup>1</sup>; R. C. Glass<sup>1</sup>; C. H. Carter, Jr.<sup>1</sup>; <sup>1</sup>Cree, Inc, Matls. R&D, 4600 Silicon Dr., Durham, NC 27703 USA

High purity, semi-insulating (HPSI) 4H-SiC crystals with diameters up to 75mm have been grown by the seeded sublimation growth technique without the intentional introduction of elemental deep-level dopants, such as vanadium. Wafers cut from these crystals exhibit homogeneous activation energies near mid-gap and thermally stable semi-insulating behavior (>1E9 Ω-cm) throughout device processing. Secondary ion mass spectroscopy, deep level transient spectroscopy, and electron para-

magnetic resonance data suggest that the semi-insulating behavior originates from deep levels associated with intrinsic point defects. The room-temperature thermal conductivity of this material is near the theoretical maximum of 5 W/cmK for 4H-SiC, 4x higher than that reported for GaN, and 15x higher than that of sapphire. Devices fabricated on these HPSI wafers do not exhibit any substrate related back-gating effects and have power densities as high as 5.2 W/mm. This work was supported in part by DARPA, BMDO, and ONR.

## 2:40 PM

**JJ5, ZnO Substrates for Optoelectronic Devices:** *Jeff Nause*<sup>1</sup>; Bill Nemeth<sup>1</sup>; <sup>1</sup>Cermet, Inc., Crystal Growth, 1019 Collier Rd., Atlanta, GA 30318 USA

There has been growing interest in ZnO recently due to its potential applicability to optoelectronic devices such as light emitting and laser diodes, which cover a wide visible range from red to blue. The tendency for the material to decompose at high temperature has inhibited crystal growth using conventional melt growth processes. In this present effort, a high-pressure, induction-melting technique was used to melt zinc oxide. The high-pressure process prevents the decomposition of the zinc oxide, while a proprietary melt containment technique serves to contain the ~1975°C melt without introducing impurities. The ability to obtain a pool of molten ZnO enables large diameter ZnO to be crystallized using conventional melt growth processes. ZnO has been melted in 6 inch diameter crucibles, producing kilogram-sized boules of ZnO, from which centimeter-sized single crystals were solidified. The bulk growth technique used eliminates the problem of crucible reactivity, and crystal contamination. Wafers have been fabricated from melt-grown boules and used for oxide and nitride epitaxy. The growth details, and characterizations of ZnO single crystals will be discussed.

## 3:00 PM Break

## 3:20 PM

### JJ6, Determination of GaN Polarity by Interaction with H<sub>2</sub> Remote Plasmas:

*Maria Losurdo*<sup>1</sup>; M. M. Giangregorio<sup>1</sup>; Pio Capezzuto<sup>1</sup>; Giovanni Bruno<sup>1</sup>; Gon Namkoong<sup>2</sup>; W. A. Doolittle<sup>2</sup>; April S. Brown<sup>2</sup>; <sup>1</sup>Istituto di Metodologie Inorganiche e dei Plasmi, IMIP-CNR, via Orabona, 4, Bari 70126 Italy; <sup>2</sup>Georgia Institute of Technology, Sch. of Electl. & Compu. Eng., Microelect. Rsrch. Ctr., Atlanta, GA 30332-0269 USA

In the last decade, GaN has received significant attention for its use in optoelectronic and high power/temperature electronic devices. GaN is suitable for applications such as UV detectors, ultraviolet-blue LEDs and laser diodes. Moreover, the high electron velocity and thermal conductivity of GaN make it well suited for high power/temperature heterojunction FETs. Nevertheless, being non-centro-symmetric due to its wurtzitic structure, GaN films show the phenomenon of polarity, i.e., GaN can be Ga-polar ([0001] direction) or N-polar ([000-1] direction). Spontaneous polarization and piezoelectric polarization depend on the film polarity, which needs to be known and controlled—particularly for FETs. In fact, it is well known that Ga- and N-polarity yield GaN films with vastly different structural, optical, and electronic properties. Different methods have been proposed and demonstrated to determine the polarity of GaN films. The formation of a 2° at an epitaxial AlGaIn barrier is a reliable but indirect method, and wet etching methods (by NaOH, KOH or H<sub>3</sub>PO<sub>4</sub>) are destructive and do not allow the distinguishing of samples with different densities of inversion domains (IDs), or with different defect densities. Herein, we present a new highly-selective process based on the interaction of GaN with H-atoms from a remote plasma source. We infer that the efficacy of this approach is related to the mixed polarity (or I.D. density) nature of the surface, and uses the different surface reactivity of hydrogen with the N-face versus the Ga-face of GaN. This process produces different etching by-products on these faces, NH<sub>3</sub> and gallane, respectively, with different volatility. This process yields Ga-enrichment that further blocks the etching process. Hence, it can be considered non-destructive since only a few tens of nanometers are involved in this reactive process, and the surface morphology is not changed. The high polarity selectivity inherent in this process, combined with measurements of surface potential by Kelvin probe force microscopy (KPFM), allows to distinguish films with the same polarity, but with different inversion domain (IDs) densities. Furthermore, different atomic H etching behaviour is found for IDs in comparison to dislocations. X-ray photoelectron spectroscopy (XPS) and Spectroscopic ellipsometry (SE) data are also presented to corroborate the process. With the KPFM

data, we correlate the chemistry of the GaN surface modification induced by the atomic H dry etching to the film polarity and IDs. GaN films with different polarities and ID densities are grown by MBE using a multistep (substrate nitridation-buffer growth-annealing-bulk growth) process and are analysed. The film polarity is discussed in relation to different growth parameters, such as substrate nitridation and the GaN/AlN buffer layer sequence in order to achieve a better control of film properties. Specifically, it is demonstrated that Ga-polar GaN films (with IDs) can be grown by MBE on sapphire substrate by controlling the substrate nitridation step and the buffer layer.

### 3:40 PM Student

**JJ7, Study on Sapphire Surface Preparation for III-Nitride Heteroepitaxial Growth:** *Fransiska Dwikusuma*<sup>1</sup>; Dovas Saulys<sup>2</sup>; Thomas F. Kuech<sup>1</sup>; <sup>1</sup>University of Wisconsin–Madison, Cheml. Eng., 1415 Engineering Dr., Madison, WI 53706 USA; <sup>2</sup>University of Wisconsin–Madison, Matls. Rsrch. Sci. & Eng. Ctr., 7303 Chemistry Bldg., Madison, WI 53706 USA

The surface preparation of sapphire for III-nitride heteroepitaxial growth remains a critical consideration for improvement of the epitaxial film quality. The chemical treatment of sapphire has been used to remove polishing damage and prepare the surface for subsequent epitaxial growth. The resulting sapphire surface serves to nucleate the GaN epitaxial layer and the detailed structural and chemical nature of the surface determines, in large part, the defect structure of the overlying GaN layer. We have undertaken a detailed study of the effects of wet chemical etching on the resulting morphology of the sapphire substrate. The effect of temperature and time on etching behavior and resulting surface was determined for several conventional surface preparations. In the present study, the etching of *c*-plane sapphire substrates using H<sub>2</sub>SO<sub>4</sub>, H<sub>3</sub>PO<sub>4</sub>, and a 3:1 H<sub>2</sub>SO<sub>4</sub>:H<sub>3</sub>PO<sub>4</sub> mixture as a function of temperature and etching time was studied using atomic force microscopy. The sapphire treatments by liquid etching were compared with H<sub>2</sub> etching at 1100°C and air-annealing at 1400°C. The detailed chemical and structural result of the chemical etching was a function of the chemical composition and the specific time and temperatures used in the treatment. The sapphire etch rate in an acidic solution is determined by temperature, etching time, solubility of the etching product, and the acidity of the solution. The rates of liquid-based etch increased exponentially with temperature. Pure sulfuric acid exhibits the highest etch rate at temperatures higher than 200°C. The optimum surface morphology was obtained when the sapphire was etched in H<sub>2</sub>SO<sub>4</sub> at 300°C for 30 minutes. Under these conditions, the initial surface scratches were removed without forming surface pits with the surface roughness decreasing. Etching at a higher temperature or longer period generated insoluble mixture of Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> and Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>·17H<sub>2</sub>O deposits on the surface. Phosphoric acid and the 3:1 H<sub>2</sub>SO<sub>4</sub>:H<sub>3</sub>PO<sub>4</sub> mixture preferentially etched defects at the sapphire surface, forming pits on the surface. The pits became larger as the etching temperature and time increase. H<sub>2</sub> treatment at 1100°C removed surface contaminants but did not etch the surface damage. Air-annealing at 1400°C for 1 hour gave the best surface morphology, where the surface was atomically smooth and exhibited surface steps. The results of this study were described in terms of the chemistry of the sapphire etching process.

### 4:00 PM

**JJ8, Effect of Chemical Treatment on the Electronic Properties of (0001) GaN Surface:** *Julia W. Hsu*<sup>1</sup>; Hock M. Ng<sup>1</sup>; A. M. Sergent<sup>2</sup>; <sup>1</sup>Lucent Technologies, Bell Labs., 600 Mountain Ave., Murray Hill, NJ 07974 USA; <sup>2</sup>Agere Systems, Matls. Rsrch., 600 Mountain Ave., Murray Hill, NJ 07974 USA

The change in surface electronic properties of GaN films after being treated with different chemical cleaning procedures is evaluated using a scanning Kelvin force microscope (SKFM). The GaN films were grown by plasma assisted molecular beam epitaxy on sapphire substrates. The n-type film is Ga polar, 5 μm thick, and doped with Si at a concentration of 4E17 cm<sup>-3</sup>. A scanning Kelvin force microscope measures the contact potential difference (CPD) between the surface of the sample and the conducting probe tip. CPD equals (W<sub>tip</sub>-W<sub>sample</sub>)/e, where W<sub>tip</sub>(sample) is the work function of the tip(sample) and e is the fundamental electronic charge. W<sub>tip</sub> can be obtained by measuring CPD on several metals with known work functions. Defining ΔCPD as the change in CPD after chemical treatment, we find that cleaning in acids (HCl and H<sub>3</sub>PO<sub>4</sub>) produces negative ΔCPD, i.e. increases average W<sub>sample</sub>. Cleaning in bases (KOH and NH<sub>4</sub>OH) produces the opposite trend. This trend is consistent

with having a dipole layer adsorbed on the GaN surface. Surface photovoltage was observed for all surfaces. Most interestingly, we find that potential variation near threading dislocations can be revealed by treating the sample in hot H<sub>3</sub>PO<sub>4</sub> for 5 min. SKFM images of “native” GaN surface show very little contrast. After cleaning in H<sub>3</sub>PO<sub>4</sub>, there is no noticeable change in the topography while the overall CPD decreases by 100 to 150 meV and the localized reduction of CPD are visibly associated with edge dislocations. Reduction of CPD corresponds to negative fixed charges. In contrast, negative charges were not seen for screw dislocations with any of the treatments. These results indicate that (1) the surface Fermi level of GaN is not strongly pinned, (2) the occupation number of the defect states can be changed by chemical treatments, and (3) edge and screw dislocations have gap states at different energies. Since both the positions and distribution associated with surface states and dislocations are sensitive to intrinsic as well as extrinsic factors, we would not expect the same chemical treatment to produce the same CPD changes or contrast in different samples.

### 4:20 PM

**JJ9, Late News**

### 4:40 PM

**JJ10, Late News**

## Session KK:

### Non-Destructive Testing and *In-Situ* Monitoring and Control

Friday PM

Room: MultiCultural Theatre

June 28, 2002

Location: University of California

*Session Chairs:* Mark Goorsky, University of California–Los Angeles, Dept. of MSE, 6531 Boelter Hall, Los Angeles, CA 90095 USA; Kurt Eyink, US Air Force, 3005 P St., Ste. 6, AFRL/MLPS, Wright-Patterson AFB, OH 45433 USA

### 1:20 PM Student

**KK1, *In Situ* Control of Reactive Ion Etching of Patterned Silicon Using Real Time Spectroscopic Ellipsometry:** *Sang-Jun Cho*<sup>1</sup>; Paul G. Snyder<sup>1</sup>; Natale J. Ianno<sup>1</sup>; Craig M. Herzinger<sup>2</sup>; Blaine Johns<sup>2</sup>; <sup>1</sup>University of Nebraska–Lincoln, Dept. of Electl. Eng., 209N Walter Scott Eng. Ctr., Lincoln, NE 68588-0511 USA; <sup>2</sup>J. A. Woollam Company, R&D, 645 M St., Ste. 102, Lincoln, NE 68508 USA

*In situ* optical techniques such ellipsometry and reflectometry have been increasingly used for control of etching of thin films. In this work we use real time spectroscopic ellipsometry (RTSE) during reactive ion etching (RIE) to monitor and control the etch depth into a silicon substrate, rather than through a thin film. To monitor etching into a substrate, patterning is necessary to produce lateral interference between reflections from the masked and unmasked areas. Undoped Si was patterned with photoresist (PR) in a linear grating pattern, with 20 μm linewidth and 40 μm period. It was then reactive ion etched in a CF<sub>4</sub>-O<sub>2</sub> plasma at a pressure of 100 mTorr, with RF power in the range of 25-100 W. During the etching RTSE data were collected and simultaneously analyzed for etch depth, and etching was stopped when the fitted etch depth reached its target value, 500nm. The model used for RTSE data analysis assumes spatial coherence of the light beam over an area which is large compared to the grating period, but it does not explicitly include diffraction effects. The etch rates of Si and PR were also determined, based on the real time fit results. *Ex situ* spectroscopic ellipsometry (SE) measurements were also made before and after etching. The final etch depth was also confirmed by scanning electron microscopy (SEM) measurement. The final etch depths obtained by all the methods were in very good agreement. In addition to real time etch depth control, Si etch rate as a function of RF power was determined without interrupting the etching or replacing the Si wafer. RTSE data were continuously taken as RF power was varied in the range of 25-100 W. Etch rates obtained from RTSE agreed well with the etch rates determined from individual etch runs. This demonstrates the ability to rapidly determine etch rate as a

function of RF power or other variables, within a single etch run. Research supported by ONR Grant No. N00014-01-1-0742.

#### 1:40 PM

**KK2, Characterization of the Optical Properties of BeZnTe Thin Films Using Spectroscopic Ellipsometry:** *Frank C. Peiris*<sup>1</sup>; Matthew R. Buckley<sup>1</sup>; O. Maksimov<sup>2</sup>; M. C. Tamargo<sup>2</sup>; <sup>1</sup>Kenyon College, Dept. of Physics, Gambier, OH 43022 USA; <sup>2</sup>City College & Graduate Center of CUNY, Dept. of Chem., New York, NY 10031 USA

Due to its superior p-type doping characteristics as well as its ability to form a lattice with high degree of covalent bonding, BeZnTe has recently been proposed for applications in lasers and LEDs that operate in the visible wavelength range. We have investigated the dielectric response of a series of BeZnTe thin films in which the Be concentration ranged from 0-52%. The thin films of BeZnTe were grown on InP substrates using molecular beam epitaxy. Initially, these films were analyzed by X-ray diffraction experiments to determine their alloy concentrations using the lattice parameter values. A rotating analyzer spectroscopic ellipsometer was employed to measure the complex reflection ratio in air at room temperature for each of the films in the energy range between 1.2-6.0 eV. Using a standard inversion technique, the experimental data were modeled to obtain the dielectric function for each of the BeZnTe samples. This immediately allows one to determine the index of refraction of these films which is of great interest if they are to be used in optoelectronic applications. Furthermore, by analyzing the imaginary part of the dielectric constant data we have deduced the critical point parameters by assigning oscillators corresponding to the electronic transitions in the Brillouin zone. We also verified that the direct band gap of the BeZnTe alloys follows a linear dependence on the alloy concentration which can be expressed as  $E(x)=2.23*(1-x) + 4.06*x$ . This relationship obtained by the ellipsometric data is consistent with the result determined from photoluminescence and reflectivity data.

#### 2:00 PM

**KK3, A Combined In-Situ and Ex-Situ Analysis of Hydrogen Radical and Thermal Removal of Native Oxides from (001) GaAs:** *Kurt G. Eynik*<sup>1</sup>; Larry Grazulis<sup>1</sup>; <sup>1</sup>Air Force Research Laboratories, AFRL/MLPS, 3005 P St., Ste. 6, Wright Patterson AFB, OH 45433 USA

We are currently involved in the re-growth on nano-patterned GaAs surfaces. The nano-patterning is accomplished in air by a diamond tip held with a constant force. Native oxides are present on these surfaces and introduce an obstacle to the subsequent regrowth. Therefore the removal of this oxide is the first step for the re-growth of thin layers on these patterned surfaces. In this study we used in-situ spectroscopic ellipsometry (SE) and reflection high energy electron diffraction (RHEED) as well as ex-situ atomic force microscopy to follow the hydrogen cleaning and thermal removal of the native oxides from the GaAs surface. SE and RHEED were used to follow the oxide desorption process in-situ and were used to determine when the surface was clean. Post AFM analysis indicated that the thermally desorbed oxide surface contained pits which were approximately 100Å deep and covered 15% of the surface. Hydrogen cleaning was studied at substrate temperatures between 400-535°C using a pressure of  $\sim 1 \times 10^{-6}$  Torr and a cracking thermocouple reading of 900°C. The time to produce a clean surface was found to decrease as the temperature was increased. At the highest temperatures, cleaning took less than 10 minutes. AFM analysis indicated smooth surfaces were produced up to 500°C. Above 500°C pitting was seen to occur similar to that observed for thermal oxide desorption. It was found that this pitting only occurred after spectroscopic ellipsometry indicated that the surface was being modified.

#### 2:20 PM

**KK4, Micro-Raman Investigation of the N-Dopant Distribution in Lateral Epitaxial Overgrown GaN/Sapphire (0001):** *Vladimir V. Chaldyshev*<sup>1</sup>; Fred H. Pollak<sup>1</sup>; M. Pophristic<sup>2</sup>; S. Gou<sup>2</sup>; I. Ferguson<sup>3</sup>; <sup>1</sup>City University of New York Brooklyn College, Physics, 2900 Bedford Ave., Brooklyn, NY 11210 USA; <sup>2</sup>Emcore Corporation, 145 Belmont Dr., Somerset, NJ 08873 USA; <sup>3</sup>Georgia Institute of Technology, Sch. of Electl. & Compu. Eng., Atlanta, GA 30332-0250 USA

Lateral epitaxial overgrowth (LEO) is a commonly used technique to grow GaN films on the sapphire (0001) substrates. In this technique a SiN or SiO<sub>2</sub> mask is deposited on the substrate or GaN buffer layer, so that the material grows first in the mask windows and then over the mask stripes. Properties of the GaN film in the areas of window and stripe

should be different. It is well known that the overgrown (wing) material contains much lower density of threading dislocations. Different local environments and growth regimes also result in different background doping of the window and wing material. We report a micro-Raman study of the n-dopant distribution in the overgrown and window regions of several LEO GaN films. Enhanced background doping (up to  $6 \times 10^{17}$  cm<sup>-3</sup>) was revealed in the wing area of the GaN films grown over the wide SiN stripes, whereas the doping level in the window area was lower and close to our detectivity threshold. The enhanced background n-doping of the wing area is most likely due to Si originated from the SiN mask. The films were grown by MOCVD on 2-inch sapphire (0001) substrates using SiN masks with different geometry. Nominal thickness of the LEO GaN films was 2 μm, however, the overgrown wings were either coalesced or separated by grooves, depending on the stripe width. The Raman study was mainly focused on the coupled longitudinal optical (LO) phonon-plasmon mode (LPP+), which provides numerical information on the local concentration of free electrons. The Raman scattering was measured in back-scattering configuration with spatial resolution of about 2 μm and excitation at 514.5nm. Due to the low background electron concentration and low layer thickness, extraction of the relevant Raman signal was challenging experimental task. In order to eliminate the contribution of the sapphire substrates from the Raman spectra of LEO samples, a technique based on confocal measurements was developed. It was followed by additional line shape analysis to distinguish the contribution of GaN buffer layers and depletion regions. The electron concentration that we have obtained in the overgrown region may have a number of important ramifications. For instance, conductive areas of GaN are obviously undesirable in any device applications with lateral electron transport, such as field effect transistors. It should be also noted that if the electron concentration could be reduced to the background level of low  $10^{16}$ cm<sup>-3</sup>, it would result in an increase of thermal conductivity (from  $\sim 1.4$  W/cm K to  $\sim 2$ W/cm K). In conclusion, using micro-Raman study we have evaluated the local background concentration of free electrons in thin LEO GaN films grown on sapphire substrates. Depending on the growth conditions and mask geometry, the local carrier concentration can be as high as  $\sim 6 \times 10^{17}$  cm<sup>-3</sup>, i.e. considerably higher than previously estimated. Either appropriate control of the growth conditions or the use of more chemically stable mask, such as Ti, may be suggested to suppress the phenomenon.

#### 2:40 PM

**KK5, Spectroscopic Characterization of Chem-Mechanically Polished and Thermally Annealed N-Type 4H-SiC:** *Bahram Roushani*<sup>1</sup>; Uma Ramabadrani<sup>1</sup>; Diana Phillips<sup>1</sup>; William C. Mitchell<sup>2</sup>; C. L. Neslen<sup>2</sup>; <sup>1</sup>Kettering University, Sci. & Math., 1700 W. Third Ave., Flint, MI 48504-4898 USA; <sup>2</sup>Wright Patterson Air Force Base, Air Force Rsrch. Lab., Matls. & Mfg. Direct., Dayton, OH 45433 USA

The effects of surface polishing and thermal annealing on n-type 4H-SiC single-crystals were analyzed by spectroscopic measurements. The inertness and mechanical properties of the SiC materials introduce various challenging problems in surface polishing and surface preparation of SiC for device fabrications. Raman spectroscopic measurements provided information about the bulk properties, while X-ray photoelectron spectroscopy (XPS, a.k.a. ESCA) produced information about the surface properties of crystalline SiC samples treated by polishing and annealing processes. We have investigated single crystal nitrogen doped 4H:SiC with doping range of  $2-3 \times 10^{18}$  cm<sup>-3</sup>. Si terminated surfaces of the SiC wafers were prepared by mechanical polishing (MP) and by chem-mechanical polishing (CMP). The polished samples were thermally processed using rapid thermal annealing (RTA) and furnace annealing (FTA) in an argon atmosphere. Both sets of MP and CMP samples were annealed up to 1100°C using RTA, while a set of CMP samples were also annealed using FTA up to 1600°C. Four peaks in XPS spectra representing the Si, C, N, and O chemical environment were analyzed in our studies. Investigation of the coupled phonon-plasmon Raman mode, which is sensitive to carrier concentration and electron mobility, shows shifts in MP case compared to the CMP case with annealing temperature in the range of 800°C to 1000°C. The XPS data of MP samples showed that between 1000°C and 1100°C the carbon and oxygen bonding is varied and there is evidence of more oxycarbide formation for this type of polishing. The effect was less pronounced in the MP case over the same temperature range. The experiment on the CMP sample indicates that the oxycarbide content on the surface increases with FTA for tem-

peratures above 1100°C, while the peak intensity of the bridging oxygen becomes increases with temperature up to 1200°C, and then decreases with further increase in annealing temperature. The same samples studied by Raman spectroscopy indicate an increase in the out of plane stress with temperature. Comparing the results from various experiments, we find that in general CMP sample display more uniform surface morphology compared with the MP samples. The optimal annealing temperature for our samples is found to be in the range of 1000°C-1100°C when an argon atmosphere is used. For samples that need to be subjected to a higher temperature, the annealing atmosphere may be varied or a subsequent anneal performed at lower temperatures may prevent the incorporation of excess non-bridging oxygen.

### 3:00 PM Break

### 3:20 PM Student

**KK6, Cathodoluminescence In-Depth Spectroscopy Study of AlGaIn/GaN Heterostructures:** *Fumitaro Ishikawa*<sup>1</sup>; Hideki Hasegawa<sup>1</sup>; <sup>1</sup>Hokkaido University, Rsrch. Ctr. for Integrated Quantum Elect. & Grad. Sch. of Elect. & Info. Eng., Kital3 Nishi8, Kita-ku, Sapporo 060-8628 Japan

Cathodoluminescence (CL) provides depth-resolved information by changing the electron acceleration voltage. Paying attention to this, we have recently proposed the CL in-depth spectroscopy (CLIS) technique as a non-destructive characterization method of buried hetero-interfaces. Here, a plot of CL intensity as a function of the electron acceleration voltage is defined as the CLIS spectrum, and is analyzed on computer by a self-consistent Scharfetter-Gummel vector-matrix program for processes of carrier drift/diffusion, generation through Everhart-Hoff electron energy loss curves, and radiative and non-radiative SRH bulk/surface/interface recombination. In this paper, the CLIS spectroscopy technique is applied to GaN epitaxial wafers and AlGaIn/GaN hetero-epitaxial wafers in order to obtain information on the distributions and properties of bulk and surface defects in those important materials. N-type GaN(2µm) epitaxial wafers and Al<sub>0.3</sub>Ga<sub>0.7</sub>N(30nm)/GaN(1µm) hetero-epitaxial wafers were grown by the MOVPE method on sapphire substrates with low temperature GaN buffer layers (30nm). On the measured CL spectra of both samples, three CL peaks, namely, the GaN band edge emission (BEE) peak at 3.42eV, a broad and strong yellow luminescence (YL) peak at 2.20eV and an additional very sharp peak at 1.79eV, were clearly observed. The third peak at high acceleration voltages (15-35kV) was identified to be due to Cr<sup>3+</sup> ions in the sapphire substrates. AlGaIn BEE peak was not be seen in AlGaIn/GaN sample. CLIS spectra for BEE and YL peaks from the GaN sample had stretched shapes than calculated ideal spectra, and showed rapid fall-off at low acceleration voltages (1-3 kV). The CLIS spectrum shape for YL in AlGaIn/GaN samples was strongly dependent on 2<sup>θ</sup>, although that for GaN BEE itself was independent of 2<sup>θ</sup> and was very close to the ideal shape. With 2<sup>θ</sup>, the YL shape followed that of the GaN BEE. Without 2<sup>θ</sup>, the shape became double peaked with the minimum appearing near the maximum position for the case with 2<sup>θ</sup>, being similar to Bradley et al. Detailed computer analysis led to the following conclusions: (1)High density U-shaped surface states with particular charge neutrality levels exist on surfaces of GaN and AlGaIn. They cause stretching and fall-off of CLIS spectra and vanishing of AlGaIn BEE. (2)AlGaIn layer acts like a surface passivation layer for GaN BEE leading to nearly ideal spectrum shape. (3)Defects responsible for YL are bulk deep levels uniformly distributed in the GaN layer rather than surface/interface defects. Dependence of YL spectrum shape on 2<sup>θ</sup> can be explained in terms of rate limiting process for YL reflecting change in minority carrier profile caused by the strong polarization surface field inducing 2<sup>θ</sup>. The result directly indicates that YL is due to transition from the conduction band to YL deep acceptors such as V<sub>Ga</sub> rather than that from deep donors to the valence band.

### 3:40 PM Student

**KK7, Characterization of the Effects of Device Fabrication on AlGaIn/GaN Layers with Spatially Localized LEEN Spectroscopy:** *Gregg H. Jessen*<sup>1</sup>; B. D. White<sup>1</sup>; S. T. Bradley<sup>1</sup>; P. E. Smith<sup>1</sup>; L. J. Brillson<sup>1</sup>; J. E. Van Nostrand<sup>2</sup>; R. Fitch<sup>3</sup>; G. D. Via<sup>3</sup>; J. K. Gillespie<sup>3</sup>; R. W. Dettmer<sup>3</sup>; J. S. Sewell<sup>3</sup>; <sup>1</sup>Ohio State University, Electl. Eng., 205 Dreese Lab., Columbus, OH 43210 USA; <sup>2</sup>Air Force Research Laboratory, 2241 Avionics Cir., WPAFB, OH 45433-7322 USA; <sup>3</sup>Air Force Research Laboratory, Sensors Direct., 2241 Avionics Cir., WPAFB, OH 45433-7322 USA

Uniformity and reliability of contact performance to AlGaIn/GaN materials are of major importance to the development of GaN devices for

RF applications. Lack of control over defects in these systems results in low yield and large variations in device operation. Furthermore, the effects of device processing on defects inherent in the material are relatively unknown. While other researchers have done much work to characterize the effects of etching on contacts to AlGaIn/GaN, we assume that low temperature processing steps, such as those used for lithography, have no effect on GaN which is intended for use as robust high-temperature devices. In order to reduce defects and to improve control over device processing, it is necessary to understand the nature of these defects at the affected device location. We present spatially localized Low Energy Electron-Excited Nano-Luminescence (LEEN) Spectroscopy as a relatively non-destructive technique to obtain information about defects as they occur at a device location by measuring optical defect emissions in the vicinity of the test structure in question. Previously, defects associated with optical emissions from yellow luminescence have been shown to correlate with ohmic contact performance. Using LEEN's depth dependence, we find the defects are concentrated near the top 50nm of the sample. The optical measurements were taken in an ultra-high vacuum SEM so the wafers could be analyzed in the center of the largest gap on the same Transmission Length Method (TLM) test structure for each die. In this work, we investigate the effects of HEMT fabrication on LEEN defect emissions of AlGaIn/GaN device layers. We observe a reduction of defect emissions at 2.20eV from yellow luminescence and defect emissions at 3.1 eV associated with Mg impurities during high temperature anneals at 800°C in nitrogen for ohmic contact formation. We observe a further reduction in these deep level defect emissions after baking at 270°C in air with a PMGI mask for gate lithography. Conversely, we observe an increase in the deep level defect emission at 3.1 eV after annealing unprocessed samples in air at 270°C without PMGI. We also find that the relative increase in deep level defect emission after the air anneal is directly related to the average contact resistance obtained over 60 die distributed over 4 wafers after fabrication. Whether the processing degrades or enhances the device structures, we have shown that even low temperature processing steps comparable with local operating temperatures of high power RF devices appear to change defect properties. Ultimately this can lead to changes in devices and variations in performance during operation. These experiments show that the variation can be monitored prior to fabrication as an indicator of potential device performance. Underlying physical mechanisms will be discussed.

### 4:00 PM

**KK8, Advanced X-Ray Scattering and Imaging Techniques for Semiconductor Wafer Characterization:** *Tilo Baumbach*<sup>1</sup>; Petr Mikulik<sup>1</sup>; Dusan Korytar<sup>1</sup>; Petra Pernot<sup>1</sup>; Daniel Luebbert<sup>1</sup>; Martin Herms<sup>1</sup>; Lukas Helfen<sup>2</sup>; Christof Landesberger<sup>3</sup>; <sup>1</sup>Fraunhofer Institute for Nondestructive Testing, Krügerstrasse 22, Dresden 01326 Germany; <sup>2</sup>ESRF, ave. des Martyrs, Grenoble 38042 France; <sup>3</sup>Fraunhofer Institut fuer Zuverlaessigkeit und Mikrointegration, Hansastrasse 27d, Muenchen 80868 Germany

Wafer quality inspection and defect analysis are crucial for improvements of the wafer fabrication technology as well as the correlation of device properties with the processes of wafer treating. The presentation demonstrates trends of X-ray imaging and scattering techniques with conventional and synchrotron radiation sources and the capability of detailed quality inspection of wafers concerning their structural perfection. Synchrotron X-ray diffraction imaging techniques are applied to characterize grown-in and process-induced defects as well as stresses. We present results for different semiconductor materials (SiC, GaAs, InP and Silicon) and different fabrication technologies. The following examples are in the focus of discussion: 1)the detection of surface damage, generated by surface grinding of thick and ultra-thin wafers and removed in subsequent technological steps; 2)quantitative imaging of lattice deformation caused by wafer gluing; 3)detection of periodic dislocation networks generated by wafer bonding; 4)quantitative imaging of lattice deformations and macroscopic defects by micrometer resolved tilt maps; 5)precipitation in low temperature grown GaAs studied by anomalous small angle X-ray scattering. Main results related to grinding damage and removal by spin etching have been obtained by a)X-ray monochromatic section topography with its high sensitivity to (sub-micron) defects through the visibility of fringes, b)high resolution monochromatic double crystal topography with its high sensitivity to strain and diffuse scattering at the tails of rocking curves. Micrometer resolved three dimensional tilt mapping allowed to study quantitatively the influence of dislocation

lines, lineages and macroscopic defects on warpage and mesoscopic tilt and curvature in correlation with the microscopic defect structure and its lateral distribution.

## Session LL: Epitaxial Oxides on Silicon

Friday PM Room: UCEN State Street  
June 28, 2002 Location: University of California

*Session Chairs:* Laura Wills Mirkarimi, Agilent Technologies, Inc., Bldg. 26M-7, 3500 Deer Creek Rd., Palo Alto, CA 94304 USA; Eric Garfunkel, Rutgers University, Dept. of Chem., Piscataway, NJ 08854 USA

### 1:20 PM Invited

**LL1, Silicide/Oxide Heteroepitaxy—A Barrier Offset Study for a Crystalline Dielectric on Silicon:** *Rodney McKee*<sup>1</sup>; <sup>1</sup>Oak Ridge National Laboratory, Metals & Ceram. Div., Bldg. 4500S, MS 6118, Oak Ridge, TN 37831-6118 USA

We have asked the questions: Does charge transfer and dipole formation at an oxide semiconductor interface depend on epitaxy? If so, how is the Schottky barrier influenced? Our data and theory answer these questions, and we can report that structure-specific charge transfer processes lead to Schottky barrier formation and modification for a dielectric/semiconductor interface. The variation in the electrostatic potentials across the interface can be explained as charge transfer associated with layer sequencing and epitaxy-specific chemical bonding.

### 2:00 PM

**LL2, Epitaxial Silicon-Insulating Metal Oxide Heterostructures:** *Supratik Guha*<sup>1</sup>; Vijay Narayanan<sup>1</sup>; Nestor Bojarczuk<sup>1</sup>; Lars-Ake Ragnarsson<sup>1</sup>; <sup>1</sup>IBM, T. J. Watson Rsrch. Ctr., Rsrch., Rt. 134 & Kitchawan, Yorktown Heights, NY 10514 USA

Silicon-insulator heterostructures are attractive for a variety of purposes: ultrathin silicon on insulator, alternate gate dielectrics, and three dimensional integration applications for silicon microelectronics, as well as silicon based luminescent structures and novel silicon quantum well based devices. There are two classes of oxides that can be epitaxially grown on silicon with the orientational relation dictated by the oxygen sublattice—the bixbyite (and related) oxides of the rare earth metals that are epitaxial to Si(111), and the perovskite oxides that are epitaxial on Si(100). Yttrium oxide has been a much studied epitaxial oxide on Si(111) with a lattice mismatch that is 2.5% smaller than twice the silicon lattice constant. In this work, via X-ray diffraction measurements and TEM studies on MBE grown films, we show that by adding small amounts of La to Y<sub>2</sub>O<sub>3</sub>, a homogeneous La-Y oxide may be grown such that the lattice constant can be controllably increased to exactly match twice the lattice constant of silicon. The growth mode of these oxides on silicon is two dimensional and uniform ultrathin epitaxial oxide films may be grown by this process. We further show that ultrathin uniform silicon epitaxial layers may also be grown on top of these epitaxial oxides for quantum well based applications. These results, and the role of the initial growth mode for oxide on silicon and silicon on oxide epitaxy, will be discussed.

### 2:20 PM

**LL3, Atomistic Calculation of Leakage Current Through Ultra-Thin Metal-Oxide Barriers:** *Leonardo R. Fonseca*<sup>1</sup>; Xiaodong Zhang<sup>2</sup>; Alexander A. Demkov<sup>2</sup>; <sup>1</sup>Motorola, Inc., Semiconductor Product Sector, 2200 W. Broadway, Mesa, AZ 85202 USA; <sup>2</sup>Motorola, Inc., Physl. Sci. Rsrch. Lab., 7700 S. River Pkwy., Tempe, AZ 85284 USA

Combining first-principles molecular dynamic simulations and non-perturbative scattering theory for transport calculations, we study leakage current through ultra-thin crystalline metal-oxide and SiO<sub>2</sub> barriers. The results are compared to semi-classical WKB calculations. Moreover we calculate leakage current in the presence of impurities and crystal defects commonly found in metal-oxide barriers.

### 2:40 PM

**LL4, Epitaxial Growth of Uniformly (100)-Oriented Lanthanum-Substituted Bismuth Titanate Thin Films on Electroded Silicon Substrates:** *Ho Nyung N. Lee*<sup>1</sup>; Dietrich Hesse<sup>1</sup>; Nikolai Zakharov<sup>1</sup>; Ulrich Goesele<sup>1</sup>; <sup>1</sup>Max Planck Institute of Microstructure Physics, Exp. Dept. II, Weinberg 2, Halle/Saale 06120 Germany

Ferroelectric bismuth-layered perovskite films are presently being studied for use in digital memory systems. Numerous investigations of polycrystalline films, such as SrBi<sub>2</sub>Ta<sub>2</sub>O<sub>9</sub> (SBT) and La-substituted Bi<sub>4</sub>Ti<sub>3</sub>O<sub>12</sub> (BLT), have been stimulated by potential applications in ferroelectric nonvolatile memories. This application potential is in large part based on the high fatigue endurance of these materials. However, the application of polycrystalline films suffers from certain limitations. For instance, randomly oriented polycrystalline films may result in an unacceptable cell-to-cell variation in a large capacitor array when the lateral size of the ferroelectric cells is below 100nm as required for Gigabit memories. Conceptually, the use of epitaxial films should allow to overcome this non-uniformity problem of ferroelectric properties. Due to their highly anisotropic, epitaxial thin films of these materials can easily be grown with the [001] axis perpendicular to the film plane. However, *c*-axis-oriented films have no (or a negligibly small) polarization component along the film normal. Therefore, recent worldwide efforts have concentrated on the growth of epitaxial films in one of the so-called non-*c*-axis orientations. Orientations of these kind are, e.g. (118) and (104) for BLT or (116) and (103) for SBT, with the spontaneous polarization vector being inclined to the film plane. The best choice would, however, be *a*-axis-oriented films, because here the (major) polarization vector would be perpendicular to the film plane resulting in a maximum value of the remanent polarization. Such *a*-axis-oriented films have so far, however, been grown only on rather special complex-oxide single crystal substrates (mostly without bottom electrodes) which are not suitable for microelectronic applications. Moreover, to enable the integration of bismuth-layered perovskite films into silicon-based microelectronics, the growth of uniformly *a*-axis-oriented films on electroded Si substrates is necessary and has been a long-standing challenge so far. In this presentation the epitaxial growth and characterization of uniformly *a*-axis-oriented ferroelectric BLT thin films having the major spontaneous polarization entirely along the film normal will be reported. The films have been grown using pulsed laser deposition on buffered Si(100) substrates covered with bottom electrodes. The use of epitaxially strained SrRuO<sub>3</sub> bottom electrode layers of well-defined specific thickness and crystallographic orientation, and of particular “kinetic” deposition conditions to suppress the bismuth re-evaporation during deposition are essential to grow purely *a*-axis-oriented BLT thin films. The orientation and microstructure of the grown films are investigated by X-ray diffraction and transmission electron microscopy. Investigations of ferroelectric hysteresis loops revealed that the *a*-axis-oriented BLT films have a remanent polarization of 32  $\mu\text{C}/\text{cm}^2$ —a new record value for bismuth-layered perovskite thin films.

### 3:00 PM Break

### 3:20 PM Student

**LL5, Heteroepitaxial Growth of Conducting Perovskite Oxides on Silicon:** *James Lettieri*<sup>1</sup>; Jeff Haeni<sup>1</sup>; Darrell Schlom<sup>1</sup>; R. Ramesh<sup>2</sup>; X. Q. Pan<sup>3</sup>; <sup>1</sup>Pennsylvania State University, Dept. of Matls. Sci. & Eng., 129 MRI-Rsrch. Park, University Park, PA 16802 USA; <sup>2</sup>University of Maryland, Dept. of Matls. & Nuclear Eng., 1108 Chem. & Nuc. Eng. Bldg., College Park, MD 20742 USA; <sup>3</sup>University of Michigan, Dept. of Matls. Sci. & Eng., 2038 Dow Bldg., Ann Arbor, MI 48109 USA

The growth of epitaxial perovskites on silicon presents significant opportunities to harness the anisotropic and versatile properties of multicomponent oxides while simultaneously exploiting the properties of the underlying semiconductor. For complete integration, direct manipulation of an epitaxial oxide’s functionality through the semiconductor is a key criterion. We address the question of the bridge between oxide and semiconductor through the use of epitaxial conductive perovskites grown directly on silicon. Conducting perovskites (such as La-doped SrTiO<sub>3</sub> and SrRuO<sub>3</sub> explored in this work) play a two-fold role; they act as templates for the growth of more complex oxide structures and they form a direct conduit between the semiconductor and functional oxide. Here, conducting, epitaxial perovskite oxides were grown by MBE and used to integrate ferroelectric and piezoelectric Pb(Zr,Ti)O<sub>3</sub>. Issues con-

cerning the epitaxial growth of these oxides on silicon will be described through RHEED, X-ray diffraction, and TEM analysis. Electrical characterization including I-V and ferroelectric hysteresis and piezoresponse of the integrated Pb(Zr,Ti)O<sub>3</sub> will be presented.

### 3:40 PM

**LL6, Nanoscale Phenomena in Epitaxial Perovskite Oxides on Silicon:** V. Nagarajan<sup>1</sup>; S. Prasertchoung<sup>1</sup>; A. Stanishefsky<sup>1</sup>; B. T. Liu<sup>1</sup>; K. Maki<sup>1</sup>; J. Melngailis<sup>1</sup>; Ramamoorthy Ramesh<sup>1</sup>; James Lettieri<sup>2</sup>; J. H. Haeni<sup>2</sup>; Darrell G. Schlom<sup>3</sup>; Wei Tian<sup>4</sup>; Xiaoqing Pan<sup>4</sup>; <sup>1</sup>University of Maryland—College Park, Matls. & Nuclear Eng., College Park, MD 20742 USA; <sup>2</sup>Pennsylvania State University, Matls. Sci. & Eng., 129 MRI-Rsrch. Park, University Park, PA 16802 USA; <sup>3</sup>Pennsylvania State University, Matls. Sci. & Eng., 103 Steidle Bldg., University Park, PA 16802-5005 USA; <sup>4</sup>University of Michigan, Matls. Sci. & Eng., Ann Arbor, MI 48109-2136 USA

The growth of epitaxial perovskites on silicon presents significant opportunities to harness the anisotropic and versatile properties of multicomponent oxides while simultaneously exploiting the properties of the underlying semiconductor. For complete integration, direct manipulation of an epitaxial oxide's functionality through the semiconductor is a key criterion. We are using the ferroelectric/piezoelectric perovskite, lead zirconate titanate (PZT), as a prototypical test vehicle to create model heterostructures to probe the ferroelectric and piezoelectric responses at the nanoscale. These studies are facilitated by a focused ion beam milling process that enables us to routinely fabricate sub-micron test structures (with the smallest size of the order of 70nm). In this paper, we present results of piezoelectric and ferroelectric measurements on such nanoscale capacitors. We show that at such a nanoscale it is indeed possible to harness the intrinsic piezoelectric response of the ferroelectric layer, simply by removing all mechanical constraints. Secondly it is possible to evaluate the contribution of extrinsic phenomenon such as domain wall movement to the ferroelectric and piezoelectric behavior. Thus, the focus of the presentation is on ferroelectric phenomenon at the nanoscale, where novel and exciting effects have been investigated. This work is supported by the NSF-MRSEC under contract No. 00-80008.

### 4:00 PM Invited

**LL7, Compound Semiconductors on Silicon: A Breakthrough Technology:** William J. Ooms<sup>1</sup>; <sup>1</sup>Motorola Laboratories, Matls., Device, & Energy Rsrch., 2100 E. Elliot Rd., Tempe, AZ 85284 USA

The combination of the superior electrical and optical performance of III-V compound semiconductors with mature silicon technology is an exciting new technology for the semiconductor industry. The successful integration of the III-V compound semiconductors with silicon opens the door to significantly less expensive optical communications, high-frequency radio devices and high-speed microprocessor-based subsystems by potentially eliminating the current cost barriers holding back many advanced applications. For consumers, the technology should result in smarter electronic products that cost less, perform better and have exciting new features. The technology will change the economics and accelerate the development of new applications, such as broadband "fiber" cable to the home, streaming video to cell phones and automotive collision avoidance systems. Other potential markets include data storage, lasers for such consumer products as DVD players, medical equipment, radar, automotive electronics, lighting, and high efficiency photovoltaics. Until now, there has been no way to combine light-emitting semiconductors with silicon integrated circuits on a single chip, and the need to use discrete components has compromised the cost, size, speed and efficiency of high-speed communications equipment and devices. In this presentation, the recent development of III-V compound semiconductor materials on silicon substrates at Motorola Labs will be reviewed. Materials and device results will be discussed.

### 4:40 PM

**LL8, Interface Engineering in the Si-SrTiO<sub>3</sub>-GaAs Stack:** Alex Demkov<sup>1</sup>; Xiaodong Zhang<sup>1</sup>; Jamal Ramdani<sup>1</sup>; Lyndee H. Tisinger<sup>1</sup>; Dirk Jordan<sup>1</sup>; <sup>1</sup>Motorola, Inc., Physl. Scis. Rsrch. Labs., 7700 S. River Pkwy., Tempe, AZ 85284 USA

Two major challenges in hetero-epitaxial growth are the lattice and chemical bonding mismatch at the interface of two disparate materials. In most applications a two-dimensional (2D) layer-by-layer growth is a must to achieve a high quality film necessary to make electronic or optical devices. We use the first-principles pseudopotential density functional approach to investigate the thermodynamic stability of the Si-

SrTiO<sub>3</sub> and SrTiO<sub>3</sub>-GaAs interfaces, and determine the wetting conditions under various chemical environments. First, we describe several Si-STO interfaces that while being thermodynamically unstable provide wetting of Si by the perovskite layer and should therefore result in the 2D layer by layer (Frank-van der Merwe) growth. We have also investigated the band discontinuity at this interface. Second, we describe the SrTiO<sub>3</sub>-GaAs interface. We have found that GaAs does not wet SrTiO<sub>3</sub> if the bulk termination of both materials is maintained. Several structures resulting in wetting are found, however. In particular, the use of the Al surface modifying layer results in wetting. The transition layer formed at the interface is related to the Zintl-Klemm intermetallic compound and opens a new avenue in the oxide-semiconductor interface engineering.

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## Session MM: Novel Fabrication of Nanostructures

Friday PM                      Room: Corwin West  
June 28, 2002                Location: University of California

*Session Chairs:* Ben V. Shanabrook, Naval Research Laboratories, Nanostructures Sect., Code 6870, Washington, DC 20375-5000 USA; Mark Miller, University of Utah, 122 S. Central Campus Dr., Rm. 304, Salt Lake City, UT 84112-0560 USA

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### 1:20 PM Student

**MM1, Ordering of Quantum Dots Using Genetically Engineered Bacteriophage:** Seung-Wuk Lee<sup>1</sup>; Chuanbin Mao<sup>1</sup>; Christine E. Flynn<sup>1</sup>; Angela M. Belcher<sup>1</sup>; <sup>1</sup>The University of Texas at Austin, A5300, Dept. of Chem. & Biochem., Austin, TX 78712 USA

A liquid crystal system was used for the fabrication of a highly ordered composite material using genetically engineered M13 bacteriophage and ZnS nanocrystals. The bacteriophage, which formed the basis of the self-ordering system, were selected to possess a specific recognition moiety for ZnS crystals. The bacteriophage were coupled with ZnS solution precursors and spontaneously evolved a self-supporting hybrid film material that was ordered at the nanoscale and at the micrometer scale into ~72 micrometer domains, which were continuous over a centimeter length scale. In addition, suspensions were prepared in which the lyotropic liquid crystalline phase behaviors of the hybrid material were controlled by solvent concentration and by the use of a magnetic field. We anticipate that nano- and multi-length scale alignment of hybrid organic-inorganic materials using recognition as well as a liquid crystalline self-ordering system may provide new and inexpensive pathways to organize important electronic and optical materials.

### 1:40 PM

**MM2, Noble Metal-Peptide Interactions: A Novel Biomediated Route to Metallic Nanoparticles:** Daniel J. Solis<sup>1</sup>; Brian D. Reiss<sup>1</sup>; Angela M. Belcher<sup>1</sup>; <sup>1</sup>University of Texas at Austin, Dept. of Chem. & Biochem., 4.220 Welch Hall, Austin, TX 78712 USA

The specific binding of proteins to inorganic materials is an exciting new means of achieving controlled nucleation, growth and ordering of nanoparticles. Using the evolutionary peptide selection methods developed by Belcher et. al., the noble metals have been screened against a 12 amino acid bacteriophage library. Sequences with high binding affinities have been isolated and studied via optical methods. The noble metals, (gold, silver and copper) are consistently used in spectroscopic surface studies, and will aid in the determination of peptide-substrate interactions. Surface Plasmon Resonance and Second Harmonic Generation Spectroscopy have been used to probe the kinetics and relative strengths of peptide binding. The absorption and subsequent reduction of gold and silver salts by biological systems is an important area of research in bioremediation and nanotechnology, and it is believed that the selected peptides for the noble metals will provide a low temperature route to the synthesis of highly regular metallic nanoparticles.

### 2:00 PM Student

**MM3, Selective MBE Growth of High Density GaAs/AlGaAs Hexagonal Nanowire Network Structures on Pre-Patterned GaAs Substrates:**

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For realization of high-density large-scale quantum integrated circuits (Q-LSIs) based on semiconductor quantum nano-structures, it is necessary to form high-density network structures containing quantum wires (QWRs) and quantum dots (QDs). The purpose of this paper is to realize high-density GaAs/AlGaAs hexagonal close-packed QWR network structures by selective MBE growth on pre-patterned GaAs substrates. Such structures are useful for implementing high-density logic circuits having the binary-decision diagram logic architecture which is particularly suited for quantum devices, as recently proposed and demonstrated<sup>[1,2]</sup>. Pre-patterning was done on semi-insulating (001) GaAs substrates by electron-beam (EB) lithography and wet chemical etching. After thermal surface cleaning under As pressure, GaAs/AlGaAs materials were supplied on to patterned substrates. To optimize the growth conditions to grow uniform QWRs, growth of <-110>-oriented QWR was first investigated. Growth of a GaAs buffer layer on the patterned substrates led to formation of a ridge structure array with (113)/(111) facets. Subsequent growth of AlGaAs reduced the extension of top (113) facet region with growth time. The mechanism was found to be due to that fact that the growth rate on top (113) facet is three times larger than that on the side (111) facet. Further growth of GaAs (10nm)/AlGaAs (300nm) layers led to self-organized formation of an embedded GaAs QWR on each ridge top. The wire width could be successfully reduced from 260nm down to 40nm. Intense and sharp PL peaks (FWHM 23 meV) were obtained, indicating formation of highly uniform QWRs. As the substrate pattern to form hexagonal networks, two combinations of pattern directions were investigated. They were a combination of <-110>- and <100>-orientations and that of <-110>- and <510>-orientations. Under the optimal conditions, two kinds of GaAs/AlGaAs hexagonal networks with good surface morphology were selectively formed with the hexagon density of  $1 \times 10^7$ - $1 \times 10^8$  cm<sup>-2</sup>. Detailed SEM and AFM studies have shown that networks combining <-110>- and <510>- oriented wires poses better surface morphology. In PL and CL measurements on the <-110>-<100> network structure, only emission from <-110> wire segments was observed at 1.57 eV, and that from the <100> wire segments was missing probably due to poor wire formation. On the other hand, two sharp emissions at 1.57 eV and 1.54 eV were seen in the <-110>-<510> network structure, and they were identified to come from <-110> wire and <510> wire segments. CL measurements also indicated that both embedded QWR segments are connected to each other within the structure. It seems feasible to increase the hexagon density up to  $1 \times 10^9$ - $1 \times 10^{10}$  range by further optimization of growth conditions. <sup>[1]</sup>S. Kasai, Y. Amemiya and H. Hasegawa: Tech. Dig. 2000 IEEE, IEDM (2000) 585; <sup>[2]</sup>H. Hasegawa and S. Kasai: Physica E, 11 (2001) 149.

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**MM4, Controlled Deposition of II-VI Nanostructures:** *Timo Schallenberg*<sup>1</sup>; Claus Schumacher<sup>1</sup>; Tanja Borzenko<sup>1</sup>; Georg Schmidt<sup>1</sup>; Laurens Molenkamp<sup>1</sup>; <sup>1</sup>Universität Würzburg, EP III, AM Hubland, Würzburg 97074 Germany

We demonstrate the potential of shadow growth to obtain well-defined nanostructures. The resolution of this selective area epitaxy (SAE) technique is limited by partial shadows and self-assembling due to surface diffusion. In molecular beam epitaxy diffusion lengths are normally of the order of micrometers, but we have observed that motion is extremely directional in the case of II-VI semiconductors (under group V-rich conditions), due to their surface reconstruction. Diffusion lengths are very short in [1-10] direction, thus enabling the growth of sharply defined nanostructures. In order to control the extend of partial shadows  $\Delta x = h \tan(\Delta\theta)$  we use shallow (stationary) shadow masks (h:250nm-5 $\mu$ m) developed from AlGaAs/GaAs layers on GaAs [001] substrate. Additionally we have minimized the angular spread  $\Delta\theta$  of the molecular beams to below 1° by reducing the apertures of the effusion cells. Consequently the growth area below the masks is precisely defined to a few nanometers. *In situ* lateral structuring with stationary masks is achieved by varying the angles of the incident molecular beams. In this way it is possible to modify doping and composition within one layer, to shift it laterally, and even to split it. Additionally we have investigated an effect (compound enhanced sticking) based on zero sticking of the single elements at growth temperature. Due to reevaporation growth is mainly restricted to the overlap of the molecular beams. Therefore the growth area is not mere a projection of the masks aperture, but can be freely

adjusted. In this contribution we present two types of experiments, which demonstrate the potential of this technique. First we have used stationary shadow masks with stripe-apertures for the fabrication of MgZnSse-embedded ZnSe and CdZnSe quantum-well wires. With photolithographically prepared masks we were able to obtain homogeneous nanostructures, which showed intense cathodoluminescence at room temperature. In a similar experiment a nominal CdSe-wire was embedded in ZnSe, resulting in the area-selective formation of quantum-dots in a line. In another experiment we have used 2D nanostructured shadow masks for the controlled deposition of CdZnSe quantum-dots (without self-assembly). A ZnSe-mesa was grown through a stripe aperture, while the dots were deposited through neighbouring aperture-holes. Due to the enhanced sticking of the compounds the size of the dots is defined by the overlap of the cadmium and selenium molecular beams incident through different holes.

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**MM5, Sparse Kinked Si Nanowires Growth Catalyzed by TiSi<sub>2</sub> Islands in Gas-Source MBE:** *Qiang Tang*<sup>1</sup>; Xian Liu<sup>2</sup>; Theodore I. Kamins<sup>3</sup>; Glenn Solomon<sup>4</sup>; James S. Harris<sup>4</sup>; <sup>1</sup>Stanford University, Matls. Sci. & Eng., CIS Receiving, Stanford, CA 94305 USA; <sup>2</sup>Stanford University, Matls. Sci. & Eng., CIS-126X, Stanford, CA 94305 USA; <sup>3</sup>HP Laboratories, Quantum Sci. Rsrch., 1501 Page Mill Rd., MS 1123, Palo Alto, CA 94304-1126 USA; <sup>4</sup>Stanford University, Electl. Eng., CIS-X Rm. 311, Stanford, CA 94305 USA

As devices in modern integrated circuits become smaller and smaller, the fabrication process become increasingly expensive, and sub-100nm feature sizes become difficult to produce. New nano-scale assembling technology, such as catalyzed nanowires growth and quantum dot growth, may benefit integrated-circuit production by eliminating critical lithography step. In these self-assembled systems, small features are formed using chemical reactions and/or crystal growth with limited or coarse lithography. Using TiSi<sub>2</sub> islands as a catalyst, we have grown Si nanowires in molecular-beam epitaxy (MBE) using Si<sub>2</sub>H<sub>6</sub> as a gas source. Approximately one monolayer of Ti was deposited on Si(001) wafers at 500°C and then annealed above 800°C to form TiSi<sub>2</sub> islands. The Si nanowires were then grown at 500°C using Si<sub>2</sub>H<sub>6</sub> gas as the Si source. Utilizing reflection high-energy electron diffraction (RHEED) and scanning electron microscope (SEM) observations, most TiSi<sub>2</sub> islands are C49 phase with the orientation: Si[110]//C49-TiSi<sub>2</sub>[100] (~6% lattice mismatch) and Si(001)//C49-TiSi<sub>2</sub>(010). These islands are relaxed and they do not nucleate Si nanowires, possibly due to a highly defective interface with the Si substrate. The Si nanowires, nucleated by other differently oriented C49 TiSi<sub>2</sub> islands, selectively grow up. One observed orientation between C49 TiSi<sub>2</sub> islands and Si lattice is Si(111)//C49-TiSi<sub>2</sub>(021) (1.7% lattice mismatch), parallel to the growth direction, and the TiSi<sub>2</sub> islands are strained to match the Si lattice. The silicon nanowires are typically between 20 and 40 nanometers in diameter and several hundred nanometers long. Normally the growth directions are <112>. The nanowires changed their growth direction several times during growth, resulting in complex RHEED patterns, which match simulated RHEED patterns calculated assuming that the nanowires change their direction by twinning along (111) planes. The twinning mechanism is confirmed by our transmission electron microscope (TEM) observations. The twinning and kinking of the Si nanowires are possibly caused by lattice mismatch stress between the TiSi<sub>2</sub> islands and the Si nanowires since TiSi<sub>2</sub> islands remain in the solid state at 500°C. Under the lattice mismatch stress, a Shockley partial dislocation can start from the island-nanowire interface and glide through Si nanowire. If the Shockley partial dislocations glide through every parallel {111} plane, a twin crystal will form. Otherwise, a highly defective crystal will form, which is also observed by TEM. After the twin is formed, it will grow together with the nanowire. When the twin is large enough to dominate, the wire will change growth direction to the new <112> direction of the twin crystal, resulting in a kink.



## Session NN: Metal Contacts to Semiconductors

Friday PM                      Room: Corwin East  
June 28, 2002                Location: University of California

*Session Chairs:* Lisa Porter, Carnegie Mellon University, Dept. of Matls. Sci. & Eng., 5000 Forbes Ave., Pittsburgh, PA 15213-3890 USA; Suzanne Mohney, Pennsylvania State University, Dept. of Matls. Sci. & Eng., 109 Steidle Bldg., University Park, PA 16802 USA

### 1:20 PM Student

**NN1, Interface Fermi Level Unpinning in Schottky Contacts on N-Type Gallium Arsenide with a Thin Low-Temperature-Grown Cap Layer:** *Saurabh Lodha*<sup>1</sup>; Nien-Po Chen<sup>2</sup>; David B. Janes<sup>1</sup>; <sup>1</sup>Purdue University, Sch. of Electl. & Compu. Eng., Box 271, 1285 EE Bldg., W. Lafayette, IN 47907-1285 USA; <sup>2</sup>Purdue University, Dept. of Physics, 1396 Physics Bldg., W. Lafayette, IN 47907-1396 USA

Schottky contacts to stoichiometric *n*-GaAs have fixed interface barrier heights of nearly 0.8 eV, due to interface Fermi level pinning.<sup>1</sup> Also, the surface of *n*-GaAs oxidizes rapidly upon air exposure whereas low-temperature-grown GaAs (LTG:GaAs) oxidizes much more slowly, with a time constant of hours.<sup>2</sup> *Ex-situ*, non-alloyed Ohmic contacts using thin LTG:GaAs surface layers on GaAs have been realized at micron<sup>3</sup> and nanometer<sup>4</sup> scales, with specific contact resistances close to  $1 \times 10^{-7}$  Wcm<sup>2</sup>. In contrast to samples with prolonged air exposures and possible mid-gap Fermi level pinning<sup>5</sup>, the samples considered in these studies<sup>2-4</sup> were exposed for relatively brief times (20-60 minutes) following either removal from the growth chamber or an oxide strip preceding metallization. Modeling of the contact performance<sup>6</sup> indicates that the interface barrier height is lower than that expected from mid-gap Fermi level pinning. However, a direct quantitative understanding of the interface Fermi level behavior in metal/*n*-GaAs structures employing LTG:GaAs interface layers is needed. The Schottky barrier behavior of a thick *n*-GaAs layer, capped by a thin (3.5 nm) layer of as-grown unintentionally or Be-doped LTG:GaAs, both grown by MBE, has been studied. Non-alloyed, *ex-situ* Schottky contacts using three metals were fabricated on the LTG:GaAs-capped layers and on *n*-GaAs control samples, to study the interface barrier height versus the metal work-function. High frequency capacitance-voltage measurements indicate a change of nearly 0.6 eV in the barrier height for the LTG:GaAs-capped samples, as compared to 0.1 eV for uncapped *n*-GaAs control samples, when the metal is varied from Ni to Mg. An effective depletion capacitance, computed using device simulations that included the charge due to mid-gap As antisite defect states in the LTG:GaAs layer, was used to fit experimental data and extract the barrier height. Current-voltage and current-temperature measurements indicate near ideal diodes and yield barrier heights in good agreement with the C-V values, with an effective Richardson constant of  $3 \times 10^4$  Am<sup>2</sup>K<sup>-2</sup>. The density of pinning states in LTG:GaAs contacts is an order of magnitude lower than in *n*-GaAs contacts and can be attributed to the short air exposure time between oxide strip and metallization. Hence, a variable Schottky barrier height, which can be controlled by changing the metal work-function and by extrinsically reducing the interface state density, indicates that the interface Fermi level for *n*-GaAs contacts can be unpinned by using a thin LTG:GaAs interfacial layer. <sup>1</sup>C. A. Mead, et al., J. Appl. Phys. 34, 3061 (1963); <sup>2</sup>T. B. Ng, et al., Appl. Phys. Lett. 69, 3551 (1996); <sup>3</sup>M. P. Patkar, et al., Appl. Phys. Lett. 66, 1412 (1995); <sup>4</sup>T. Lee, et al., Appl. Phys. Lett. 76, 212 (2000); <sup>5</sup>T. Holden, et al., Phys. Rev. B 58, 7795 (1998); <sup>6</sup>N. P. Chen, et al., J. Appl. Phys. 88, 309 (2000).

### 1:40 PM Student

**NN2, Investigations of Plasma Surface Treatment and its Sequence on the Ohmic Contact on P-GaN:** *Chee Leong Lee*<sup>1</sup>; Eng Fong Chor<sup>1</sup>; Leng Seow Tan<sup>1</sup>; <sup>1</sup>National University of Singapore, Electl. & Compu. Eng., 119260 Singapore

GaN and related compounds are attractive materials for optoelectronic and high power electronic devices. Consequently, it is crucial to

develop high-quality p- and n-type ohmic contacts on GaN to enhance their performance. We have found that plasma surface treatment can be a useful processing step in forming an ohmic contact on p-GaN. The metallization scheme used is Pd/Ni/Au. The samples given a plasma treatment using N<sub>2</sub>/Cl<sub>2</sub> (flow rates of 5/25 sccm at pressure of 8 mTorr, ICP power of 500 W, RIE power of 100 W, chuck temperature of 25°C), with or without a subsequent aqua regia treatment, yield better I-V characteristics than the sample treated only with aqua regia. On the other hand, the sample given a Cl<sub>2</sub> (30 sccm) plasma treatment has shown the worst characteristic. Recent studies in the literature have shown that Cl<sub>2</sub> plasma etching can lead to preferential nitrogen (N) loss from the surface of GaN. This results in N vacancies that behave like n-dopants and hence is detrimental to the formation of ohmic contacts on p-GaN. By adding N<sub>2</sub> to Cl<sub>2</sub>, excessive loss of N can be avoided. In addition, it has been reported that plasma exposure on GaN will introduce point defects in the damage region, and these point defects tend to act as deep acceptor levels which may be useful in forming a good ohmic contact for p-GaN. This could explain the improvement derived from N<sub>2</sub>/Cl<sub>2</sub> plasma treatment. It is also seen that a two-step process, i.e., N<sub>2</sub>/Cl<sub>2</sub> plasma followed by aqua regia treatment, gives better results than a single-step N<sub>2</sub>/Cl<sub>2</sub> plasma treatment. This can possibly be a consequence of damage recovery in GaN after plasma treatment due to the subsequent chemical treatment. We have also found that the sequence of plasma surface treatment is important in achieving a good ohmic contact. The sample that has been given a plasma surface treatment before photoresist coating for metallization yields better contact properties than the sample given the plasma treatment after the photoresist coating. All samples are given aqua regia chemical treatment prior to metal evaporation. The observation made in Fig. 2 could be explained as follows: The wafer temperature may rise to several hundred degrees Celsius during plasma etching and such high temperature can cause undesirable phenomena, especially when there is photoresist on the wafer, e.g., photoresist degradation. In addition, photoresist may be sputtered during plasma treatment onto the exposed region where metal will be subsequently evaporated. This can cause surface contamination and degrade contact properties.

### 2:00 PM Student

**NN3, Phase Diagrams in the Metal-III-Sb Systems for the Design of Contacts to Antimonide Based Compound Semiconductor Devices:** *Wayne Liu*<sup>1</sup>; Suzanne E. Mohney<sup>1</sup>; <sup>1</sup>Pennsylvania State University, Matls. Sci. & Eng., 206A Steidle Bldg., State College, PA 16802 USA

Antimonide based compound semiconductors are promising candidates for high frequency, low power electronic devices. These semiconductors include GaSb, AlSb and InAs, as well as their alloys with lattice constants near 6.1 Angstroms. The performance of electrical contacts to these semiconductors is a critical issue for many of the devices currently under development. The base of a heterojunction bipolar transistor, for example, will require a very shallow, low resistance ohmic contact, and we want to design ohmic contacts that react only to a specified depth within the structure of certain high electron mobility transistors. For infrared devices, alloys that include InSb are additionally of interest. To assist with the design of such contacts, we have performed thermodynamic calculations to estimate ternary phase diagrams for the transition metal-Ga-Sb, transition metal-In-Sb and selected metal-Al-Sb systems. Similar phase diagrams have been a valuable tool in the development of contacts to other III-V semiconductors, and such information is already available for many metal-In-As systems. Information is lacking, however, for many of the metal-III-Sb systems. For the metal-Ga-Sb systems, we found experimental phase diagrams only for Ni, Pd, Pt, and Au; for the Metal-In-Sb systems, only Ni and Au were found, and for the metal-Al-Sb systems, we could find no phase diagrams. In this presentation, we have categorized the predicted metal-Ga-Sb and metal-In-Sb phase diagrams according to dominant features in their tie-line configurations in order to highlight trends in the contact metallurgy across the periodic table. For comparison, we have also applied the same method for estimating the Ni-, Pd-, Pt-, and Au-Ga-Sb and the Ni- and Au-In-Sb phase diagrams for which experimentally determined diagrams were already available. Excellent agreement was found between the types of tie-line configurations predicted and determined by experiments, although minor discrepancies in some of the tie-lines were sometimes observed. According to our calculations, W, Re, and Os are the only transition metals anticipated to be in thermodynamic equilibrium with both GaSb and InSb under the conditions considered in our calculations, and W is

the only transition metal predicted to be in equilibrium with AlSb. The use of this information for the design of contacts will next be described, and the results of ongoing studies of metal/GaSb and metal/InSb contacts will be presented.

## 2:20 PM Student

**NN4, Design of a Shallow and Thermally Stable Ohmic Contact to P-Type InGaSb:** *Sammy H. Wang*<sup>1</sup>; Brett A. Hull<sup>1</sup>; Suzanne E. Mohny<sup>1</sup>; Brian R. Bennett<sup>2</sup>; <sup>1</sup>Pennsylvania State University, Dept. of Matls. Sci. & Eng., 206 Steidle Bldg., University Park, PA 16802 USA; <sup>2</sup>Naval Research Laboratory, Code 6876, 4555 Overlook Ave., Washington, DC 20375-5347 USA

Low resistance ohmic contacts to the antimonide based compound semiconductors are needed for a variety of electronic and optoelectronic devices currently under development, and a further requirement for some of these contacts will be that they are very shallow. In this presentation, we focus on the design of a shallow, thermally stable ohmic contact to p-In<sub>0.25</sub>Ga<sub>0.75</sub>Sb. It is actually not difficult to achieve ohmic contacts to p-In<sub>0.25</sub>Ga<sub>0.75</sub>Sb; Fermi level pinning typically leads to a low Schottky barrier height to p-GaSb, and the situation should be similar for p-In<sub>0.25</sub>Ga<sub>0.75</sub>Sb. Among the preliminary ohmic contacts we tested, we found that Pd-based contacts provided particularly low specific contact resistance, but interdiffusion of Pd with the semiconductor was very extensive after the contacts were annealed at 250°C for 1 hour, as determined by Auger depth profiling. Significant interdiffusion between InGaSb and Pd, Au, or some of the other common contact metals may even occur at room temperature over the course of months or years. We therefore took steps to limit the interdiffusion between Pd and InGaSb by retaining only a very thin layer of Pd (5 nm) next to the semiconductor. We selected W for the second layer in the contact because we had previously predicted that it would be in thermodynamic equilibrium with both GaSb and InSb. It is also a good candidate for a diffusion barrier between the layers. We finally capped the sample with Au because of its resistance to oxidation and high conductivity. Upon testing Pd/W/Au contacts with varying W and Au layer thicknesses, we discovered that the layer thicknesses Pd (5 nm)/W (50 nm)/Au (145 nm) offered a lower contact resistance than did contacts with thicker W and thinner Au layers. A specific contact resistance of 3 x 10<sup>7</sup> Ohm-cm<sup>2</sup> was measured for as-deposited contacts, as determined by the transfer length method (TLM). Upon further data analysis, we discovered that the measured specific contact resistance of the contacts with thicker W and thinner Au layers was artificially high due to a significant contribution from the sheet resistance of the metal film. The metal sheet resistance became important because both the interfacial and semiconductor sheet resistances were very low. The metal sheet resistance would similarly impact the performance of contacts in devices in which current is transported laterally. Fortunately, contacts with the lowest metal sheet resistance, employing only 50nm of W, exhibited very little interdiffusion and excellent electrical stability upon thermal stressing at 250°C for 30 min and 125°C for 24 hours. More severe stressing and additional materials characterization studies are underway.

## 2:40 PM

**NN5, Development of Highly Reliable Schottky in Contacts for CdTe for Radiation Detectors:** *Miki Moriyama*<sup>1</sup>; Masahiro Kunisu<sup>1</sup>; Atushi Kiyam<sup>2</sup>; Ryoichi Ohno<sup>2</sup>; Masanori Murakami<sup>1</sup>; <sup>1</sup>Kyoto University, Dept. of Matls. Sci. & Eng., Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501 Japan; <sup>2</sup>Acrorad Company, Ltd., Okinawa Plant, 13-23, Suzuki, Gushikawa-shi, Okinawa 904-2234 Japan

Cadmium telluride (CdTe) is an attractive semiconductor material for X-ray and  $\bar{\alpha}$ -ray radiation detectors, because CdTe has a large bandgap energy (~1.6eV) and a high average atomic number ( $Z_{CdTe}=50$ ). However, since CdTe has the low mobility and short lifetime of holes, a considerable amount of charge applied to the CdTe detectors are lost, causing reduction of energy resolution. To increase the charge collection, a high bias voltage must be applied to the CdTe detectors. Thus, Schottky contacts with low leakage current at a high bias voltage are required to realize high resolution CdTe detectors. Although the conventional approach to fabricate such the Schottky contacts for p-type CdTe requires the use of metals with low work function, such as indium (In), degradation of the detection sensibility during device operation, known as "polarization effect", is often observed in the CdTe detectors. In order to manufacture the CdTe radiation detectors, highly stable Schottky con-

tacts with low leakage current must be developed. The purposes of the present study are twofold. The first is to develop highly reliable Schottky In contacts for the CdTe radiation detectors. The second is to understand the Schottky In contact formation mechanism by analyzing the microstructure of the In films which were deposited at various substrate temperatures using X-ray diffraction (XRD) and transmission electron microscopy (TEM). These studies will provide us a guideline for developing the Schottky contacts for p-type CdTe. The wafers used in this study were Cl-doped CdTe single crystals with (111) orientation. The resistivity of the CdTe was about 1~2·10<sup>9</sup>Ωcm. Prior to contact depositions, the CdTe surface was chemically cleaned. Then, In films (300nm) were deposited on the Te-face of CdTe substrates. The substrate temperatures (Ts) were changed from room temperature to 400°C. After the In deposition, a Pt contact metal was deposited on the opposite surface of the wafer by electroless plating. The leakage current in the dark was measured at room temperature. The current-voltage characteristics and the performance for the radiation detectors were also measured. The deposition of In at elevated substrate temperatures decreased significantly the leakage current and improved the stability during device operation. XRD analysis showed that In atoms reacted with CdTe forming In<sub>4</sub>Te<sub>3</sub> or InTe when the In layers were deposited at temperatures higher than 200°C. The InTe contacts, which were prepared at a high depositions temperature, drastically improved the stability. TEM observations revealed that the leakage current and the stability of the CdTe radiation detectors were strongly correlated with the microstructure at the contact/CdTe interfaces.

## 3:00 PM Break

## 3:20 PM

**NN6, Comparison Study of Ohmic Contacts in Oxidizing Ambient at High Temperature for Gas Sensor Applications:** *Sang-Kwon Lee*<sup>1</sup>; Lars Uneus<sup>2</sup>; Sang-Mo Koo<sup>1</sup>; Carl-Mikael Zetterling<sup>1</sup>; Lars Gunnar Ekedahl<sup>2</sup>; Ingemar Lundström<sup>2</sup>; Anita Lloyd Spetz<sup>2</sup>; Mikael Östling<sup>1</sup>; <sup>1</sup>KTH, Royal Institute of Technology, IMIT, Dept. of Microelect. & Info. Tech., Kista, Stockholm 164 40 Sweden; <sup>2</sup>Linköping University, S-SENCE & Div. of Appl. Physics, Linköping 581 83 Sweden

High-temperature chemical sensors with fast gas response are of considerable interest for the control of combustion processes in the automotive industry. SiC based gas sensors are potential candidates for this purpose and can operate at very high temperatures due to its own superior material properties. Schottky diodes as well as field effect transistors can be used as gas sensors. Recently a metal insulator silicon carbide field effect transistor (MISiCFET) gas sensor was developed and it operated in oxidizing ambient at high temperature up to 600°C. For automotive applications, one of the essential issues limiting device performance is high temperature stable ohmic contacts to silicon carbide under these harsh environments. In this work, we will present the results of three different stacks of ohmic contacts such as TiW(180nm)/Ti(30nm)/Pt(300nm), Ni(100nm)/TaSi<sub>2</sub>(200nm)/Pt(400nm), and TaSi<sub>2</sub>(200nm)/Pt(400nm) on silicon carbide for high temperature measurements in oxidizing ambient. The ohmic contacts in TLM structures were cut in size of 2x2mm chips, and glued on heaters, where a Pt-100 element was also built in for the temperature measurement and control. Finally the contacts on heaters were mounted on a 16-pin socket, which was put in an Al-block with a gas flow channel. For this measurement, we used 20% O<sub>2</sub> in N<sub>2</sub> with a flow rate of 80 ml/min at temperatures of 500°C and 600°C. We will mainly focus on the long-term stability tests of TiW/Ti/Pt, which had the best stability and lowest contact resistivity among them. These were carried out up to 500 hours under these harsh environments. TiW/Ti/Pt contacts show a stable contact resistivity at 500°C both in vacuum and in oxidizing ambient, but they are unstable at 600°C in oxidizing ambient.

## 3:40 PM

**NN7, Nano-Graphitic Flakes and Ohmic Contact Formation on SiC:** *Weijie Lu*<sup>1</sup>; W. C. Mitchel<sup>2</sup>; W. E. Collins<sup>1</sup>; <sup>1</sup>Fisk University, Dept. of Physics, 1000 17th Ave. N., Nashville, TN 37208 USA; <sup>2</sup>Air Force Research Laboratory, Matls. & Mfg. Direct., 3005 P St., Ste. 6, Wright-Patterson AFB, OH 45433 USA

Although ohmic contacts on SiC have been studied extensively in the past decade, the mechanism of their formation on SiC is still unclear. Many metals, silicides, carbides, and borides have been examined for ohmic contact material on SiC, and the type of deposited materials seems

not be the main factor. Good ohmic contact on SiC for different materials can be formed only on highly doped SiC and after the thermal annealing process at 1000°C or above. It is well known that carbon and silicides phases are formed at high temperatures due to reactions between the metal films and SiC. Also, SiC surfaces graphitize due to preferential volatility of silicon when the annealing temperature is above 900°C. However, the effects of carbon on ohmic contact properties on metal/SiC are not understood. To understand the role of the graphitization process in ohmic contact formation on SiC, the electrical contact properties of carbon films on 4H-SiC were examined after thermal annealing. The carbon film as deposited exhibits a high electrical resistance. At annealing temperatures above 1050°C, the current-voltage curves exhibit typical ohmic contact behavior. The resistance on the carbon/SiC interface decreases with increasing annealing temperatures. It is well known that thermal annealing increases the degree of carbon graphitization and the contact behavior of C/SiC indicate the graphitized carbon can form ohmic contacts on SiC. Raman spectra indicate that the sp<sup>2</sup> carbons consist of three structures: (a) amorphous aromatic sp<sup>2</sup> carbon clusters, (b) nano-size graphitic flakes, and (c) the polyene-like carbons. The deconvoluted Raman spectra for the carbon/SiC samples after annealing are shown that Schottky contact is converted into ohmic contact when sufficient amount of nano-graphitic flakes are formed on SiC. The size ( $L_a$ ) of the graphitic flakes ranges from 3.2 to 3.7nm at varying temperatures. Since the second-order bands do not appear in the carbon/SiC samples, the nano-graphitic flakes on the carbon/SiC have not formed the three-dimensional stacking structures on the c-axis after annealing from 750°C to 1350°C. Ni has been widely used for forming ohmic contact on n-type SiC and is one of the best catalysts for graphitization. Ohmic contact on Ni/C/SiC is formed at the annealing temperature of 700°C with a specific resistance of  $1.7 \times 10^{-6} \text{ Wcm}^2$ . In summary, ohmic contact of carbon films on SiC substrates can be achieved through thermal annealing. This study experimentally demonstrates that the two-dimensional nano-graphitic flakes play a determinative role in ohmic contact formation on SiC and enhance electron transfer properties on SiC interface. The temperatures required for forming ohmic contact on SiC decrease significantly when Ni catalyst accelerates the formation of nano-graphitic flakes.

#### 4:00 PM

**NN8, Effect of Co or Ni Addition to TiAl Ohmic Contact for P-Type 4H-SiC:** *Osamu Nakatsuka*<sup>1</sup>; Ryohei Konishi<sup>2</sup>; Ryuichi Yasukouchi<sup>2</sup>; Yasuo Koide<sup>2</sup>; Masanori Murakami<sup>2</sup>; <sup>1</sup>Kyoto University, Venture Business Lab., Sakyo, Kyoto 606-8501 Japan; <sup>2</sup>Kyoto University, Dept. of Matls. Sci. & Eng., Sakyo, Kyoto 606-8501 Japan

In order to manufacture high performance SiC electronics devices, development of low resistance Ohmic contact materials for p-type SiC is one of the key issues. TiAl Ohmic contact material provided contact resistivity ( $\bar{n}_c$ ) as low as around  $1\text{E-}6 \text{ } \Omega\text{-cm}^2$  after annealing at temperatures as high as 1000°C. This high annealing temperature is not acceptable for the fabrication process due to break-down of the thin insulators. To reduce the annealing temperature to obtain low resistance TiAl contacts, we studied the effect of addition of a transition metals such as Co and Ni to the TiAl contacts on the electrical properties. The reason why we chose these metals is that Co and Ni were reported to react with SiC at lower temperature of about 600°C. P-type epilayers doped with the range from  $3\text{E}18$  to  $1\text{E}19 \text{ Al/cm}^3$  were grown on the n-type 4H-SiC(0001) substrates by Cree Research, Inc. After surface cleaning, a 10nm thick SiO<sub>2</sub> layer was formed on the substrate. The electrode patterns were made by the photolithography technique and the SiO<sub>2</sub> layer was etched by diluted HF solution. Co, Ni, and Ti layers were deposited on the substrate by an e-beam in the high vacuum chamber, and an Al layer was also deposited by a resistance heater. The samples were annealed at 800°C in an ultra high vacuum chamber for 2-30 min. This temperature is acceptable for the SiC fabrication process. The electrical properties of the contacts were evaluated by current-voltage (I-V) measurements. The specific contact resistivities were measured by a circular transmission line model (TLM). Microstructure was analyzed by an X-ray diffraction (XRD), and the surface morphology was observed by a field emission scanning electron microscope (FE-SEM) and a stylus surface profiler. The I-V characteristics of SiC/Co(35nm)/Ti(50nm)/Al(300nm) samples annealed at 800°C for 2 or 5 min showed fine Ohmic behavior. The specific contact resistivity was less than  $1\text{E-}4 \text{ } \Omega\text{-cm}^2$  after annealing at such a low temperature for a short time compared with the temperature used in the TiAl contact formation process. In the case of the SiC/Ni(x

nm)/Ti(50nm)/Al(300nm) samples annealed at 800°C, which were formed some different Ni layer thickness, the contact resistivity decreased with increasing the Ni layer thickness in the range between 8 and 25nm. This indicates that the addition of Ni to the TiAl contact material plays an important role to reduce the resistivity. In summary, the addition of Co or Ni to the TiAl contact reduced the annealing temperature to prepare Ohmic contact with the low resistivity. The reduction of annealing temperature should also improve the surface morphology compared with the TiAl contact annealed over 1000°C.

#### 4:20 PM Student

**NN9, Ta/Au Ohmic Contacts to N-ZnO:** *Haifeng Sheng*<sup>1</sup>; Sriram Muthukumar<sup>2</sup>; Nuri William Emanetoglu<sup>1</sup>; Shiwei Feng<sup>1</sup>; Yicheng Lu<sup>1</sup>; <sup>1</sup>Rutgers, The State University of New Jersey, Dept. of Elect. & Compu. Eng., Piscataway, NJ 08854 USA; <sup>2</sup>Rutgers, The State University of New Jersey, Dept. of Ceram. & Matls. Eng., Piscataway, NJ 08854 USA

ZnO is a wide band-gap semiconductor that has potential applications for ultraviolet photodetectors, light-emitting diodes, and laser diodes. Ohmic contacts to ZnO is critical to the overall performance of these electronic and photonic devices. In the present work, we report the studies on ohmic contacts to epitaxially grown ZnO thin films. The unintentionally doped ZnO films were grown on R-plane Sapphire (R-Al<sub>2</sub>O<sub>3</sub>) substrates using metal-organic chemical vapor deposition. The epi-film thickness is about 300nm, and n-type carrier concentration about  $10^{17} \text{ cm}^{-3}$ . Three bilayer metallization schemes were investigated: Al/Au, Ti/Au and Ta/Au, 100nm Al, Ti and Ta were deposited directly on ZnO followed by the deposition of a 100nm Au capping layer. Transmission line method (TLM) was used to measure the specific contact resistances. The linear TLM metallization patterns were fabricated using the standard lift-off technique. For as-deposited samples, the specific contact resistances of Al/Au, Ti/Au and Ta/Au were determined to be  $1.1 \times 10^{-4} \text{ } \Omega\text{-cm}^2$ ,  $6.1 \times 10^{-4} \text{ } \Omega\text{-cm}^2$  and  $2.0 \times 10^{-4} \text{ } \Omega\text{-cm}^2$ , respectively. Annealing of all samples was conducted in a Rapid Thermal Annealing (RTA) chamber in a N<sub>2</sub> ambient. After being annealed at 300°C for 30 seconds, Al/Au showed non-linear I-V characteristics, while the specific contact resistances of Ti/Au and Ta/Au were  $6.2 \times 10^{-5} \text{ } \Omega\text{-cm}^2$  and  $4.3 \times 10^{-6} \text{ } \Omega\text{-cm}^2$ , respectively. The two samples, with Ti/Au and Ta/Au metallization schemes, were then annealed at 500°C for 30 seconds. The specific contact resistances of the Ti/Au contacts and Ta/Au contacts were increased to  $1.7 \times 10^{-4} \text{ } \Omega\text{-cm}^2$  and  $4.6 \times 10^{-5} \text{ } \Omega\text{-cm}^2$ , respectively. The 300°C annealing Ta/Au sample was further annealed successively at 500°C for 60, 120, 180 and 300 seconds. It was found that the specific contact resistance degraded to  $1.7 \times 10^{-5} \text{ } \Omega\text{-cm}^2$  after being annealed at 500°C cumulatively for a total of 660 seconds. For comparison, Ti/Au contact was investigated in similar procedures. Ti/Au started to show non-linear I-V characteristics after being annealed at 500°C for 180 seconds. Therefore, Ta/Au contacts offer lower specific contact resistance and better thermal stability than Ti/Au contacts. The surface morphology of Ta/Au and Ti/Au contacts were investigated using scanning electron microscopy. For both contact schemes, the surfaces of the as-deposited and 300°C contacts were reasonably smooth and uniform; however, the contact surface morphology changed significantly after being annealed at 500°C for 30 seconds. In the case of Ta/Au contact to ZnO, the uniformity distributed textured metallization, and, in the case of Ti/Au contact, the alloying induced pits appeared. The results of other structural characterizations, including X-ray and RBS will also be presented to correlate the electrical characteristics of the contacts with the microstructures. In conclusion, Al/Au, Ti/Au and Ta/Au contacts to n-type ZnO were investigated. The lowest specific contact resistance of  $4.3 \times 10^{-6} \text{ } \Omega\text{-cm}^2$  was achieved using Ta/Au metal contacts after annealing at 300°C for 30 seconds. The contact also shows good thermal stability.

#### 4:40 PM

**NN10, Morphological Instability of Germanosilicides on Si<sub>1-x</sub>Ge<sub>x</sub>-A Comparison Between Ni(Si,Ge) and Ti(Si,Ge):** *Tobias Jarmar*<sup>1</sup>; Johan Seger<sup>2</sup>; Ulf Smith<sup>3</sup>; Fredric Ericson<sup>1</sup>; Pererik Hellberg<sup>2</sup>; Shi-Li Zhang<sup>2</sup>; <sup>1</sup>Uppsala University, The Ångström Lab., Matls. Sci., Uppsala SE-751 21 Sweden; <sup>2</sup>Kunliga Tekniska Högskolan, Dept. of Microelect. & Info. Tech., Electrum 229, Kista SE-164 81 Sweden; <sup>3</sup>Ericsson Microelectronical AB and Uppsala University, The Ångström Lab., Matls. Sci., Kista SE-164 81 Sweden

Low-resistivity contacts to SiGe are indispensable for high-performance operation of electronic devices with SiGe, for instance, as the gate

electrode of a metal-oxide-semiconductor field-effect-transistor.  $\text{TiSi}_2$  has been widely used for low-resistivity contacts in Si devices. Difficulties in transforming the high-resistivity metastable C49 phase to the low-resistivity stable C54 phase in  $\text{TiSi}_2$ , especially in small dimension features, are one of the challenges to overcome as the critical dimensions continuously shrink. The presence of Ge in Si, i.e. SiGe alloys, has been shown to enhance the formation of the C54 phase, now in the form of a ternary alloy  $\text{Ti}(\text{Si},\text{Ge})_2$ , by decreasing the formation temperature and reducing the feature-size dependence of the C49-C54 phase transformation. NiSi has emerged as one promising candidate to replace  $\text{TiSi}_2$  for contact metallization in ultra-scaled devices. Its advantages, compared to other silicides, are low formation temperature, low specific resistivity, low contact resistivity, low Si consumption and no reported size dependence of transformation. However, NiSi is not a stable phase in contact with Si and  $\text{NiSi}_2$  forms when annealed above 750°C. In addition, the low melting point of NiSi influences its morphological stability in a negative manner. Little has been reported on how Ge affects the Ni-Si interaction. In the present study, the reaction of Ti and Ni with poly-SiGe films with various Ge contents on  $\text{SiO}_2$  is investigated.  $\text{Si}_{1-x}\text{Ge}_x$  films obtained by chemical vapor deposition were used as the substrate. The grain size of the underlying SiGe films was varied by high-temperature annealing prior to metal deposition. For the germanosilicide formation, 250-Å Ti or 200-Å Ni were deposited by electron beam evaporation. The formation was performed using Rapid Thermal Annealing (RTA) at various temperatures for 30 seconds in  $\text{N}_2$ . For the germanosilicide films formed, the sheet resistance was determined by four-point probe measurements. The sheet resistance dependence on annealing temperature for the  $\text{Ti-Si}_{1-x}\text{Ge}_x$  interaction clearly revealed that the annealing temperature needed to achieve the low resistivity germanosilicide decreased with increasing Ge content. Identification of the formed phases was carried out using X-ray Diffraction (XRD), and out-diffusion of Ge from  $\text{Ti}(\text{Si},\text{Ge})_2$  formed on  $\text{Si}_{0.53}\text{Ge}_{0.47}$  was apparent between 700 and 850°C. Morphological stability was studied by means of cross-sectional transmission electron microscopy (XTEM). As an example the  $\text{Ti}(\text{Si},\text{Ge})_2$  film formed is found not to completely cover the poly  $\text{Si}_{0.53}\text{Ge}_{0.47}$  substrate, after a 750°C anneal followed by a selective chemical etch of the surface TiN/Ti layers using a 4  $\text{H}_2\text{SO}_4$ :1  $\text{H}_2\text{O}_2$  solution at 80°C for 10 minutes. More results for comparison between  $\text{Ti}(\text{Si},\text{Ge})_2$  and  $\text{Ni}(\text{Si},\text{Ge})_2$  in terms of phase formation and morphological stability during annealing will be presented.

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