

2000 EMC At-A-Glance

Wednesday Morning, June 21, 2000

8:20 AM EMC PLENARY LECTURE/STUDENT AWARDS

Room: Sturm Auditorium

Plenary Speaker: L. L. Kazmerski, National Renewable Energy Laboratory, 167 Cole Boulevard, MS 3221, Golden, CO 80401 USA

Topic: "Photovoltaics Research and Development"

Break: 9:20 AM - 10:00 AM

<p align="center">Session A. MID-IR Devices I</p>	<p align="center">Session B. Modeling of Nano-Structures</p>	<p align="center">Session C. Polarization and Piezo- electric Effects in Nitrides</p>
<p>10:00 AM A1, The Effect of Different Interfaces on MOCVD III/AsSb Optical Properties and Device Performance R. M. Biefeld</p> <p>10:20 AM A2, High Efficiency 4.4 μm Type-II Interband Cascade Laser Stefan John Murry</p> <p>10:40 AM A3, Optical Characterization and Determination of the Band Discontinuity of the Type-II GaAsSb/InGaAs W Structure QWs Sang-Wan Ryu</p> <p>11:00 AM A4, Near-Diffraction-Limited Angled-Grating Distributed Feedback Type-II "W" Laser at 3.3 Microns Robert Ernest Bartolo</p> <p>11:20 AM A5, Lead Salt Based Vertical Cavity Surface Emitting Lasers for the 4-6 Micron Wavelength Range Thomas Schwarzl</p> <p>11:40 AM A6, Controlled Precipitation and Formation of Self-Aligned Quantum-Dot Arrays in Quasi-Binary Semiconductor Alloys Choong-Un Kim</p>	<p>10:00 AM *B1, Modeling of Nanotube Devices Francois Leonard</p> <p>10:30 AM *B2, Modeling of Transport in Carbon Nanotube Wires M. P. Anantram</p> <p>11:00 AM +B3, Self-Consistent Green's Function Theory for Molecular Electronic Devices Yongqiang Xue</p> <p>11:20 AM B4, Atomistic Simulation of Quantum Dots Including Strain and Bandstructure Gerhard Klimeck</p> <p>11:40 AM B5, Pseudopotential Calculations of Addition Energies and Optical Transitions in Charged InAs and CdSe Quantum Dots: Alberto Franceschetti</p> <p>12:00 PM B6, Late News</p>	<p>10:00 AM C1, MBE Growth and Characterization of AlGaIn/GaN Quantum Well Structures with Large Built-In Electric Fields H. M. Ng</p> <p>10:20 AM +C2, Critical Layer Thickness Determination of GaN/InGaIn Single and Double Heterostructures Mason J. Reed</p> <p>10:40 AM +C3, Exploring the Effects Tensile and Compressive Strain on 2DEG Properties with the Aid of AlInGaIn Quaternary Alloys Steven Francis LeBoeuf</p> <p>11:00 AM +C4, Piezoelectric Effects in AlInGaIn/InGaIn Quantum Well Structures Michael E. Aumer</p> <p>11:20 AM C5, Efficient Emission Against the Internal Piezoelectric Field of InGaIn/GaN/AlGaIn Single-Quantum-Well Amber Light-Emitting Diodes Shigefusa F. Chichibu</p> <p>11:40 AM C6, Bias Controlled Luminescence Efficiency in Polarized GaInN/GaN Quantum Wells Christian Wetzel</p>

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<p align="center">Session D. Photonic Bandgap Materials</p>	<p align="center">Session E. Organic Materials and Devices - I</p>	<p align="center">Session F. Oxides of Compound Semiconductors</p>
<p>10:00 AM +D1, Synthesis and Characterization of Inverse FCC Colloidal Photonic Crystals Ganesh Subramania</p>	<p>10:00 AM *E1, Mechanism of Long-Term Degradation in Small Molecule Based OLEDs Studied by Time Resolved Fluorescence Zoran D. Popovic</p>	<p>10:00 AM F1, Atomic Scale Self-Propagated Oxidation on Silicon Carbide and Abrupt SiO₂ Interface Formation P. Soukiassian</p>
<p>10:20 AM +D2, Fabrication of GaAs/AlxOy Based 3-D Photonic Bandgap Crystal by Single Step Epitaxial Growth Jayshri Sabarinathan</p>	<p>10:40 AM E2, Device Performance and Polymer Morphology in Polymer Light Emitting Diodes: The Control of Thin Film Morphology and Device Quantum Efficiency Y. Shi</p>	<p>10:20 AM +F2, Effects of Mixed Carrier Gas in Wet Thermal Oxidation of AlGaAs Yong Luo</p>
<p>10:40 AM +D3, Fabrication and Characterization of ZnSe-Based Whispering Gallery Mode Oindrila Ray</p>	<p>11:00 AM E3, High Performance Polymer Photovoltaic Cells Photodetectors and Image Sensors G. Yu</p>	<p>10:40 AM F3, Residual As and the Electrical Characteristics of AlGaAs Native Oxides for MOS Applications Pedro J. Barrios</p>
<p>11:00 AM D4, Si/SiO₂ Microcavity for Luminescence Enhancement of Er-Doped Materials Michal Lipson</p>	<p>11:20 AM E4, Nanoscale Photocurrent Spectroscopy and Mapping of Organic Semiconductors Denis Fichou</p>	<p>11:00 AM +F4, Oxidation of Antimonide-Based Semiconductors on InP Substrates Sheila K. Mathis-Yu</p>
<p>11:20 AM D5, Fabrication of a One-Dimensional Photonic Bandgap Material by Pulsed Laser Deposition René Lopez</p>	<p>11:40 AM E5, Electroluminescence of Derivatives of 8-Hydroxyquinoline Aluminum Guangming Wang</p>	<p>11:20 AM +F5, Thermal Wet Oxidation of Al_{0.4}Ga_{0.6}P John Henry Epple</p>
<p>11:40 AM D6, A Model of a Two Dimensional Photonic Bi-Oriented Crystal P. Kopperschmidt</p>		<p>11:40 AM F6, Characterization of Native-Oxide/GaN and CVD-SiNx/GaN Interfaces Tamotsu Hashizume</p>

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<p align="center">Session G. MID-IR Devices - II</p>	<p align="center">Session H. Special Topical Session</p>	<p align="center">Session I. Advanced Nitride Epitaxy</p>
<p>1:20 PM G1, Dependence of the Background Doping of InAs/(GaIn)Sb IR-Superlattices on MBE Growth Conditions <i>Frank Fuchs</i></p>	<p>1:20 PM *H1, The Design and Measurement of Molecular Electronic Switches and Memories <i>M. A. Reed</i></p>	<p>1:20 PM I1, Gallium Nitride Epitaxial Lateral Overgrowth Kinetics <i>Christine C. Willan</i></p>
<p>1:40 PM G2, Infrared Light Emitting and Negative Luminescent Devices for Enhanced Thermal Imaging <i>Tim Ashley</i></p>	<p>1:50 PM *H2, Self Assembly of Nanometer-Scale Metallic Wires for Molecular Electronics <i>Theresa S. Mayer</i></p>	<p>1:40 PM I2, Lateral Overgrowth of GaN on SiC Substrates with Vertically Conducting Buffers <i>Q. Fareed</i></p>
<p>2:00 PM G3, Epitaxial Lateral Overgrowth of CdTe on Patterned Substrates by MOVPE <i>Ruichao Zhang</i></p>	<p>2:20 PM *H3, Growth and Properties of Nanotubes <i>Hongjie Dai</i></p>	<p>2:00 PM I3, Hydrogen-Induced Changes in the Epitaxial Lateral Overgrowth of GaN <i>S. Gu</i></p>
<p>2:20 PM G4, MBE Growth and High Temperature Performance of HgCdTe Midwave Infrared Detectors <i>Terry J. deLyon</i></p>	<p>2:50 PM *H4, Digital Logic and Switching in a Quantum-dot Cellular Automata Cell <i>Gary H. Bernstein</i></p>	<p>2:20 PM I4, Lateral Epitaxial Overgrowth of GaN by Pulsed-MOCVD <i>J. Yang</i></p>
<p>2:40 PM G5, Subpicosecond Spin Relaxation in 3.6-Micron-Band-Gap InAs/GaSb Superlattices <i>Thomas F. Boggess</i></p>	<p>3:20 PM Break</p>	<p>2:40 PM +I5, Direct Lateral Epitaxy Overgrowth of GaN on Sapphire Substrate Based on Sparse GaN Nucleation Technique <i>Xingang Zhang</i></p>
<p>3:00 PM Break</p>	<p>3:40 PM *H5, Semiconductor Nanocrystals as Building Blocks for New Materials <i>Paul Alivisatos</i></p>	<p>3:00 PM Break</p>
<p>3:40 PM G6, Spectral Blue Shift and Improved Luminescence Properties with Increasing GaSb Layer Thickness in InAs-GaSb Type-II Superlattices <i>Andrew Paul Ongstad</i></p>	<p>4:10 PM *H6, Stress-Engineered Epitaxial Quantum Nanostructures <i>A. Madhukar</i></p>	<p>3:40 PM I6, Cantilever Epitaxy on Textured Substrates: A Simple Two-Step Approach to Low-Defect-Density GaN Substrates <i>Carol I. H. Ashby</i></p>
<p>4:00 PM G7, Temperature Dependence of the Fundamental Band Gaps of GaInAsSb/GaSb and GaSb <i>M. Munoz</i></p>	<p>4:40 PM *H7, Quantum Dot Based Semiconductor Laser Diodes <i>Marius Grundmann</i></p>	<p>4:00 PM I7, The Influence of Growth Parameters on Grain Size and Electrical Properties in GaN Films <i>Mark E. Twigg</i></p>
<p>4:20 PM +G8, Growth and Characterization of Sputtered Er₂O₃ Thin Films <i>Kevin M. Chen</i></p>	<p>5:10 PM *H8, Optically Probing and Controlling Single GaAs Quantum Dots <i>Daniel Gammon</i></p>	<p>4:20 PM I8, Heteroepitaxy of GaN on H-Etched SiC <i>C. D. Lee</i></p>
<p>4:40 PM G9, Late News</p>		<p>4:40 PM I9, MOCVD Regrowth of GaN on Free-Standing GaN Substrate Prepared by Hydride Vapor Phase Epitaxy <i>Ig-Hyeon Kim</i></p> <p>5:00 PM +I10, Gas Phase Chemistry of Metalorganic and Nitrogen-Bearing Compounds used in Gallium Nitride Growth <i>Ramchandra Wate</i></p>

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<p>Session J. Contacts to GaN and Other Wide Bandgap Semiconductors</p>	<p>Session K. Si-Based Heterostructures</p>	<p>Session L. Organic TFT's and Elec- tronic Transport</p>
<p>1:20 PM +J1, Characterization of Ti/Pt/Au Ohmic Contacts on p-type GaN <i>L. Zhou</i></p>	<p>1:20 PM +K1, Carrier Mobilities and Process Stability of n- and p-Surface Channel Strained Si/SiGe MOSFETs <i>Matthew T. Currie</i></p>	<p>1:20 PM *L1, Pentacene Organic Thin Film Transistors <i>Tom Jackson</i></p>
<p>1:40 PM +J2, Evidence of Band and Bending at the Surface of p-type GaN Measured by Synchrotron Radiation Photoemission Spectroscopy <i>Jong Kyu Kim</i></p>	<p>1:40 PM +K2, Post-Growth Annealing Effect on Electrical and Structural Properties of High Ge Content Si_{1-x}Ge_y/Si_{1-y}Ge_y/Si(001) P-Type Modulation Doped Heterostructures <i>Maksym Myronov</i></p>	<p>2:00 PM +L2, Crossover from Band to Hopping Transport in Organic Semiconductors <i>Hendrik Schön</i></p>
<p>2:00 PM J3, Roles of NiO Layer on Electrical Properties of NiAu-Based Ohmic Contacts for p-GaN <i>Yasuo Koide</i></p>	<p>2:00 PM +K3, High Quality Thermal Ultra-Thin Gate Oxide Directly Grown on High Temperature Formed Si_{0.3}Ge_{0.7} <i>S. B. Chen</i></p>	<p>2:20 PM +L3, Effects of Doping C₆₀ Fullerene in Diamine and Aluminumquinoline Organic Thin Films on Their Electrical Properties <i>Shizuo Fujita</i></p>
<p>2:20 PM +J4, A New Methodology for Measuring Barrier Height and Ideality Factor of Metal Contacts to p-type GaN <i>Douglas L. Hibbard</i></p>	<p>2:20 PM +K4, Germanium Photodetectors Integrated on Silicon for Si Microphotonics <i>Hsin-Chiao Luan</i></p>	<p>2:40 PM L4, Pentacene Thin Film Transistors with Photolithographically Patterned Active Layer <i>Chris D. Sheraw</i></p>
<p>2:40 PM +J5, Effect of Surface Treatment on the Change of Domain Size in Pd Contact on p-type GaN <i>Jong Kyu Kim</i></p>	<p>2:40 PM +K5, Growth of High Mobility β-FeSi₂ Continuous Films of its Conduction Type by Si/Fe Ratios <i>Ken-ichiro Takakura</i></p>	<p>3:00 PM Break</p>
<p>3:00 PM Break</p>	<p>3:00 PM Break</p>	<p>3:40 PM *L5, Recent Progress in Organic and Polymer-Based Thin Film Field-Effect Transistors <i>Zhenan Bao</i></p>
<p>3:40 PM +J6, Characterization of AlGaN Surfaces after Various Kinds of Surface Treatments <i>Shinya Ootomo</i></p>	<p>3:40 PM *K6, New Gate Dielectrics of Gd₂O₃ and Y₂O₃ Films for Si <i>J. Kwo</i></p>	<p>4:20 PM L6, Field-Effect Conductance Measurements on Microcrystals of Sexithiophene <i>Anna Chwang</i></p>
<p>4:00 PM +J7, Ohmic Contacts and Schottky Barriers to n-AlGaN <i>Eric D. Readinger</i></p>	<p>4:20 PM +K7, Epitaxial MgO Deposited on Si by Metal-Organic Molecular Beam Epitaxy using a Cubic-SiC Interlayer <i>Brent H. Hoerman</i></p>	<p>4:40 PM L7, Organic Field Effect Transistors as Vapor Sensors <i>B. K. Crone</i></p>
<p>4:20 PM +J8, NiAl as a Thermally Stable Ohmic Contact to n-GaN <i>Christopher M. Pelto</i></p>	<p>4:40 PM K8, Negative Differential Resistance with Peak to Valley Ratio Greater Than 100,000 of Double Barrier CdF₂/CaF₂ Resonant Tunneling Diode on Si(111) <i>Masahiro Watanabe</i></p>	<p>5:00 PM L8, Late News</p>
<p>4:40 PM +J9, Novel Contact System for II-VI Laser Diodes <i>Oliver Schulz</i></p>	<p>5:00 PM K9, Abrupt Oxide/Si Interface Formation Using As-Terminated Si for Ferroelectric Memory Device <i>T. Chikyow</i></p>	
<p>5:00 PM +J10, Development of Highly Reliable PdZn-Based Ohmic Contacts for p-type InP <i>Hirokuni Asamizu</i></p>		

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<p><i>Wednesday Afternoon, Cont.</i></p> <p>Session M. Transparent Conducting Oxides - I: Materials and Defect Physics</p>	<p>Session N. Epitaxy for Devices</p>	<p>Session O. Nanometer Scale Characterization</p>
<p>1:20 PM *M1, Comparison of Transparent Conducting Oxides Roy G. Gordon</p>	<p>8:00 AM +N1, Observation of Saturation Effects of As Precipitates in Large-Area MBE-Grown ITG-GaAs MSM-Photodetectors Vijay Krishnamurthy</p>	<p>8:00 AM +O1, Time Evolution Studies of the Surface Potential on LTG:GaAs Using Electrostatic Force Microscopy M. V. Batistuta</p>
<p>2:00 PM M2, Transparent Conductors in the Ga₂O₃-In₂O₃-SnO₂ System Doreen Edwards</p>	<p>8:20 AM +N2, Growth and Characterization of InAlGaP Lasers with Native-Oxide Optical and Carrier Confinement Richard D. Heller</p>	<p>8:20 AM +O2, Structural and Electronic Properties of Al_xGa_{1-x}As/GaAs Heterojunction Bipolar Transistors Characterized Using Cross-Sectional Scanning Force Microscopy P. A. Rosenthal</p>
<p>2:20 PM M3, Bulk Phase Relations, Electrical, and Optical Properties of Transparent Conducting Oxides in the CdO-In₂O₃-SnO₂ System Dan R. Kammler</p>	<p>8:40 AM N3, Comparison of Different Sources for Carbon Doping in the GaAs Base Layer of Heterojunction Bipolar Transistors Grown by LP-MOVPE T. Bergunde</p>	<p>8:40 AM O3, Observation of Coulomb Blockade and Single Electron Charging by Scanning Tunneling Spectroscopy in Artificially Patterned, Nanometer-Scale InAs Quantum Dots at 4.2K Philip Chang</p>
<p>2:40 PM +M4, Substitution and Doping Strategies in the In₂O₃ Bixbyite Host Structure Andrea Ambrosini</p>	<p>9:00 AM +N4, Bandgap Engineering via the Insertion of Strained Al_{0.7}In_{0.3} As Emitter Layers in Abrupt n-p AlInAs-GaInAs Heterojunction Bipolar Transistors Changhyun Yi</p>	<p>9:00 AM O4, Scanning Tunneling Spectroscopy Characterization of GaAs Surfaces Passivated by MBE-Grown Ultrathin Si Layers Seiya Kasai</p>
<p>3:00 PM Break</p>	<p>9:20 AM N5, Growth Temperature Dependence of 1.5µm Photoluminescence from β-FeSi₂ Balls in Si and Realization of Electroluminescence Nearly at Room Temperature Takashi Suemasu</p>	<p>9:20 AM +O5, Atomic Force Microscope Measurements of Molecular Layer Electrical Characteristics Lili Jia</p>
<p>3:40 PM *M5, Nonstoichiometric and Doped Zinc Oxide Arthur W. Sleight</p>	<p>9:40 AM Break</p>	<p>9:40 AM Break</p>
<p>4:20 PM M6, Defect Physics in ZnO S. B. Zhang</p>	<p>10:20 AM +N6, Electrical Properties of InGaAs/InP Composite-Channel Modulation-Doped Structures Grown by Solid Source Molecular Beam Epitaxy..... Tong-Ho Kim</p>	<p>10:20 AM +O6, Microcontacts to Self-Assembled Monolayers with a Conducting AFM Tip David J. Wold</p>
<p>4:40 PM +M7, Cation Distribution in the Transparent Conducting Oxide Cd_{1+x}In_{2-2x}Sn_xO₄M Donggeun Ko</p>	<p>10:40 AM N7, InAsSb as a Channel Material in High Electron Mobility Transistors Brian R. Bennett</p>	<p>10:40 AM +O7, Formation and Characterization of Nanometer-Sized Schottky Contacts on III-V Materials by In-Situ Electrochemical Process Taketomo Sato</p>
<p>5:00 PM M8, Atomic Chemical Potential Dependence of the Structural and Doping Properties of Cadmium Stannate (Cd₂SnO₄) Su-Huai Wei</p>	<p>11:00 AM +N8, Facet-Free Raised/Source Drain Contacts for Dual-Gate MOSFETs by Selective Epitaxy Thomas A. Langdo</p>	<p>11:00 AM +O8, A Physically Based Conduction Model for Ohmic Nanocontacts to GaAs Utilizing Low-Temperature-Grown GaAs Nien-Po Chen</p>
	<p>11:20 AM N9, Resonant Interband Tunneling Diodes with AlGaSb Barriers Richard Magno</p>	<p>11:20 AM O9, Late News</p>
	<p>11:40 AM N10, Lattice Rotation Determination in MHEMT Structures by High Resolution X-Ray Diffraction Abbas Torabi</p>	<p>11:40 AM O10, Late News</p>

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<p align="center">Session P. Transport Properties in Nitride Structures</p>	<p align="center">Session Q. SiC Contacts and Ion Implantation</p>	<p align="center">Session R. Silicon Integration: Thin Oxides, Alternate Dielec- trics and Epitaxial Metals</p>
<p>8:00 AM P1, Low-Temperature Electron Transport in the AlGa_N/Ga_N/AlGa_N Double Heterostructures Yulia P. Smorchkova</p>	<p>8:00 AM +Q1, Schottky Barrier Height Dependence on the Metal Work Function for p-type 4H-Silicon Carbide Sang-Kwon Lee</p>	<p>8:00 AM *R1, Reliability Characterization and Projection Issues of Sub-3nm Gate Oxides John S. Suehle</p>
<p>8:20 AM P2, Screening of Dislocation Scattering in High-Density 2D Electron Gas AlGa_N/Ga_N Heterostructures J. W. Yang</p>	<p>8:20 AM Q2, A UHV Study of Ti/SiC Schottky Barrier Formation Angela Kestle</p>	<p>8:40 AM R2, Leakage Currents in Thin Oxides and Nitrided Oxides Patrick M. Lenahan</p>
<p>8:40 AM +P3, Characterization of AlGa_N/Ga_N Lateral PiN Junctions and Schottky Rectifiers Grown by MOCVD Bryan S. Shelton</p>	<p>8:40 AM +Q3, Influence of Carrier Freeze-Out on SiC Schottky Junction Admittance Andrei V. Los</p>	<p>9:00 AM R3, Characteristics of Ultrathin SiO₂ Film Formed on Si (100) using Concentrated Ozone Gas Kunihiko Koike</p>
<p>9:00 AM +P4, Comparison of Charge Trapping Effects in AlGa_N/Ga_N Heterostructures Based on Al Composition, Doping and Growth Technique Kurt V. Smith</p>	<p>9:00 AM Q4, Low Temperature Ohmic Contacts for Vertically Conducting III-N Light Emitting Devices over SiC V. Adivarahan</p>	<p>9:20 AM R4, On the Density of States of Pb1, Si/SiO₂ Interface Centers Tetsuya D. Mishima</p>
<p>9:20 AM P5, Recombination Generation Noise and Surface States in AlGaIn_N/Ga_N-Based Field Effect Transistors Sergei Rumyantsev</p>	<p>9:20 AM Q5, Low Resistivity Ohmic Contacts to Phosphorus Ion-Implanted 4H-SiC Accomplished without Post-Deposition Annealing Satoshi Tanimoto</p>	<p>9:40 AM Break</p> <p>10:20 AM *R5, Alternative Gate Dielectrics for Advanced CMOS Devices Gerald Lucovsky</p>
<p>9:40 AM Break</p>	<p>9:40 AM Break</p>	<p>11:00 AM *R6, Optimization of a Silicon Oxide-Nitride Stack for Gate Dielectric Applications Arun Karamcheti</p>
<p>10:20 AM P6, Properties of the Channel Layer in GaN MODFETs Grown on Insulating C-doped GaN Template Layers by Reactive (Ammonia-) MBE H. Tang</p>	<p>10:20 AM +Q6, Effect of Implant Anneal and Oxidation Conditions on Nitrogen and Phosphorus Implanted 4H-SiC MOSFETs Sujit Banerjee</p>	<p>11:20 AM R7, Investigation of Implant and Anneal Modified Thermally Grown SiO₂ John F. Conley</p>
<p>10:40 AM +P7, Role of Barrier and Buffer Layer Defect States in AlGa_N/Ga_N 2DEG HEMT Structures Shawn T. Bradley</p>	<p>10:40 AM +Q7, N-Type Doping of 4H-SiC with Phosphorus Co-Implanted with C, Si and N Zhi Li</p>	<p>11:40 AM R8, Theoretical and Experimental Investigation of Ultra-Thin Oxynitrides and the Role of Nitrogen at the Si-SiO₂ Interface A. Demkov</p>
<p>11:00 AM P8, Thermal Conductivity of Fully and Partially Coalesced Lateral Epitaxial Overgrown Ga_N/Sapphire (0001) Using a Scanning Thermal Microscope D. I. Florescu</p>	<p>11:00 AM Q8, High Temperature SiC Implant Activation in a Silane Ambient to Reduce Step Bunching Galyna Melnychuk</p>	
<p>11:20 AM +P9, The Temperature Dependence of Thermal Conductivity of GaN Materials Chongyang Luo</p>	<p>11:20 AM Q9, Formation and Annealing of Ion-Implantation-Induced Defects at Low Temperatures in 6H-SiC W. Jiang</p>	
<p>11:40 AM +P10, Structural Characterization of Ga_N/AlGa_N Heterojunctions Grown by MBE Sangbeom Kang</p>	<p>11:40 AM Q10, Late News</p>	

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<p>Thursday Morning, Cont.</p> <p>Session S. Transparent Conducting Oxides II - Films</p>	<p>Session T. InGaAsN and Related Materials</p>	<p>Session U. Properties of Quantum Wires and Wells, Wires, and Superlattices</p>
<p>8:00 AM *S1, Growth Process-Doping-Microstructure-Charge Transport Relationships in Transparent Conducting Oxide Thin Films Anchuan Wang</p> <p>8:40 AM S2, A Study of the Amorphous-to-Crystalline Phase Transformation in Indium Tin Oxide David C. Paine</p> <p>9:00 AM S3, CdO Thin Films Produced by Metal-Organic Chemical Vapor Deposition with DMC and DMC-THT Precursors Xiaonan Susan Li</p>	<p>1:20 PM T1, Effect of (1,1)-DMHy Purity on MOCVD-Grown InGaAsN Performance and on Post-Growth Annealing Behavior Robert M. Sieg</p> <p>1:40 PM +T2, Influence of Nitrogen Content and Dopant Type on Deep Level Spectra of MOCVD-Grown InGaAsN Robert J. Kaplar</p> <p>2:00 PM T3, Transport Studies of Compensated InGaAsN Solar Cell Materials Steven R. Kurtz</p>	<p>1:20 PM U1, Anticorrelated Vertical Self-Organization of Stacked InAs Quantum Wires on InAlAs/InP(001) Michel Gendry</p> <p>1:40 PM +U2, Temperature Dependent Multi-Axial Strain Properties of Self-Assembled Quantum Wires David Eli Wohlert</p> <p>2:00 PM +U3, Micro-Photoluminescence Spectroscopy of Single (Al, Ga)As Quantum Wire Grown on Vicinal (110) Surfaces Takeshi Ota</p>
<p>9:20 AM +S4, Growth and Doping of Textured, Phase Pure p-type CuAlO₂ Films Renaud Emmanuel Stauber</p>	<p>2:20 PM +T4, Incorporation of Nitrogen in Group III-Nitride-Arsenides Grown by MBE Sylvia G. Spruytte</p> <p>2:40 PM +T5, High-Quality GaNAs/GaNAs Superlattices Grown by Gas-Source MBE Y. G. Hong</p> <p>3:00 PM Break</p> <p>3:40 PM T6, High Electron Mobility Transistor using GaInNAs Channel Grown by LP-MOVPE Toshihide Kikkawa</p> <p>4:00 PM T7, Exploring OMVPE-Grown InGaAsN for Electronic and Optoelectronic Devices Nein-yi Li</p> <p>4:20 PM +T8, Ga(In)NP/GaP Grown by Gas-Source MBE and Its Application for Red Light-Emitting Diodes H. P. Xin</p> <p>4:40 PM T9, Electronic Structure of Nitrogen Pairs in GaP and GaAs Paul Kent</p>	<p>2:20 PM U4, High Resolution X-Ray Diffraction from InGaAs/GaAs Quantum Dot Superlattice Structures Debdas Pal</p> <p>2:40 PM U5, Spin Lifetimes in III-V Heterostructures Wayne H. Lau</p> <p>3:00 PM Break</p> <p>3:40 PM +U6, Absorption and Photoluminescence Characteristics of MgZnO/ZnO Quantum Wells Chia-Wei Teng</p> <p>4:00 PM +U7, Si-Modulation Doped In_xGa_{1-x}As/In_{0.52}Al_{0.48}As Pseudomorphic Quantum Wells Grown on (411)A InP Substrates by MBE Issei Watanabe</p> <p>4:20 PM +U8, Preparation and Properties of AlGaIn/GaN Superlattices Uttiya Chowdhury</p> <p>4:40 PM U9, Time-Resolved Photoluminescence Studies of Al_xGa_{1-x}N/GaN Heterostructures Grown by MOCVD Ho Ki Kwon</p> <p>5:00 PM +U10, Characterization of InGaIn/GaN Multiple Quantum Well LEDs Using Surface Photovoltage Spectroscopy, Photoreflectance, and Contactless Electroreflectance B. Mishori</p>

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<p align="center">Session V. Point and Extended Defects in Mismatched Materials</p>	<p align="center">Session W. SiC Growth and Device Processing</p>	<p align="center">Session X. Silicon Integration Issues: Metallization and Low-K Dielectrics</p>
<p>1:20 PM +V1, Dislocation Glide, Blocking, and Reduction Kinetics in Compositionally Graded SiGe/Si Christopher W. Leitz</p>	<p>1:20 PM W1, Structural and Electrical Properties of 4H-SiC Epitaxial Layers Grown by Hot-Wall-CVD Guenter Wagner</p>	<p>1:20 PM +X1, Improved Shallow Junction Integrity using Single Crystalline CoSi₂ Y. H. Wu</p>
<p>1:40 PM +V2, The Role of Substrate Orientation on Misfit Dislocation Interactions Petra Feichtinger</p>	<p>1:40 PM +W2, Processing Effects of Controlled N-type and P-type Doped SiC Epitaxy for Use in Dual-Gate JFETs Michael C. David Smith</p>	<p>1:40 PM X2, Abnormal Grain Growth of Cu Film Interconnects for Si-ULSI Devices Miki Moriyama</p>
<p>2:00 PM +V3, Low-Temperature GaAs Films Grown on Ge and Ge/GeSi/Si Substrates Carrie L. Andre</p>	<p>2:00 PM +W3, Influence of Surface on Stacking Sequence Ulrike Grossner</p>	<p>2:00 PM X3, Preparation of Low-k Porous SiO₂ Films by Chemical Vapor Deposition Akira Fujimoto</p>
<p>2:20 PM +V4, Evolution of Structural and Electronic Properties of Highly Mismatched InSb Films X. Weng</p>	<p>2:20 PM W4, SiC Grown on Insulating Layers for Robust MEMS Applications J. Chen</p>	<p>2:20 PM +X4, High Frequency Characterization of Mega-Ohm Resistivity Si Formed by High-Energy Ion Implantation Y. H. Wu</p>
<p>2:40 PM +V5, Influence of Misfit Dislocations on Island Morphology in Large Lattice Mismatched Epitaxial Growth Vidyut Gopal</p>	<p>2:40 PM +W5, Radio-Tracer Identification of W- and Ta-related Deep Levels in Silicon Carbide J. K. Grillenberger</p>	<p>2:40 PM, Late News</p>
<p>3:00 PM Break</p>	<p>3:00 PM Break</p>	
<p>3:40 PM V6, The Correlation of Defect Profiles with Transport Properties of InAs Epilayers on GaP Hironori Tsukamoto</p>	<p>3:40 PM W6, Light Emission from Electron-Hole Recombination in 4H and 6H MOSFETs P. J. Macfarlane</p>	
<p>4:00 PM +V7, Influence of Misfit Dislocations on the Mobility in Pseudomorphic High Electron Mobility Transistors Based on In_xAl_{1-x}As/In_{0.75}Ga_{0.25}As/InP Structures Randy S.D. Hsing</p>	<p>4:00 PM W7, MOS Interface Characteristics for n- and p-type 4H-SiC Michael A. Capano</p>	
<p>4:20 PM +V8, Strain Relaxation and Defect Reduction in InGaAs by Lateral Oxidation of AlGaAs Channel Kuo-Lih Chang</p>	<p>4:20 PM W8, Amorphous Aluminum-Oxynitride Gate Dielectric Layers for SiC MISFET Devices Henry Luten</p>	
<p>4:40 PM +V9, Effects of Hot Electrons on Transconductance Dispersion in AlGaAs/InGaAs Pseudomorphic High Electron Mobility Transistor Kyoung Jin Choi</p>	<p>4:40 PM +W9, Etching of Silicon Carbide for Device Fabrication and Via-Hole Formation F. A. Khan</p>	
	<p>5:00 PM +W10, A Novel CMOS-Compatible Deep Etching Process for Silicon Carbide using Silicon Shadow Masks Andrew Ryan Atwell</p>	

2000 EMC At-A-Glance

Friday Morning June 23, 2000

Thursday Afternoon, Cont. Session Y. Organic Materials and Devices - II	Session Z. Ordering in Semiconductor Alloys	Session AA. Novel Optoelectronic Materials
<p>1:20 PM *Y1, Electronic Structure of Organic/Metal Interfaces Studied by Electron Spectroscopies and Kelvin Probe Kazuhiko Seki</p> <p>2:00 PM Y2, Effect of Side Groups on Electroluminescence of PPV Derivatives Guangming Wang</p> <p>2:20 PM Y3, Electroluminescent Properties of Eu-Complex Doped Organic-Inorganic Polymers A. V. Kukhta</p> <p>2:40 PM Y4, Preparation and Characterization of Polymer Gradient Glass ShenKang Ruan</p> <p>3:00 PM Break</p> <p>3:40 PM *Y5, The Interface Energetics and Growth Modes Between Organics and Indium Tin Oxide E. W. Forsythe</p> <p>4:20 PM Y6, Electroluminescence of Polymer with 8-Hydroxyquinoline Jian-Ming Ouyang</p> <p>4:40 PM Y7, Late News</p>	<p>8:00 AM *Z1, Surfactant Effects on Ordering in GaInP Grown by OMVPE Gerald B. Stringfellow</p> <p>8:40 AM Z2, Effects of Layer Thickness Fluctuations in Ordered GaInP₂ Alloys Su-Huai Wei</p> <p>9:00 AM Z3, Improvement of Electrical Characteristics of n-InGaP/n-GaAs Heterointerface using Sb Doping Grown by LP-MOVPE Toshihide Kikkawa</p> <p>9:20 AM +Z4, The Use of a Surfactant (Sb) to Induce Triple Period Ordering in GaInP Christopher M. Fetzer</p> <p>9:40 AM Break</p> <p>10:20 AM *Z5, X-Ray Diffraction Studies of Ordering in Epitaxial ZnSnP₂ S. Francoeur</p> <p>11:00 AM +Z6, Polarization Dependent Electro-Absorption Measurements—A Powerful Tool to Study Ordering Induced Changes of the Electronic Band Structure of InGaAs Jochen Spieler</p> <p>11:20 AM Z7, Investigation of Ordering in AlGaIn Alloys Eleftherios Iliopoulos</p> <p>11:40 AM *Z8, Spatial High Resolution Photoluminescence Study of Intrinsic and Self-Assembled Quantum Dots M. Wenderoth</p>	<p>8:00 AM AA1, B_{0.5}Ga_{0.5}InAs Alloys Lattice Matched to GaAs John F. Geisz</p> <p>8:20 AM AA2, Growth of Homogeneous GaAsGe Alloys by Kinetic Stabilization Andrew Gordon Norman</p> <p>8:40 AM +AA3, Highly Doped InAlP:Mg Grown by Metalorganic Chemical Vapor Deposition Yuichi Sasajima</p> <p>9:00 AM +AA4, Effects of Substrate Offset Angles on MBE Growth of ZnO (II) Keiichiro Sakurai</p> <p>9:20 AM Late News</p> <p>9:40 AM Break</p>

2000 EMC At-A-Glance

Friday Morning June 23, 2000

<p align="center">Session BB. Advances in the Growth of Quantum Dots</p>	<p align="center">Session CC. Nitride Optoelectronics</p>	<p align="center">Session DD. Nanostructure Fabrication - I</p>
<p>10:20 AM BB1, Methods for Ordering Self-Assembled InAs/GaAs Quantum dots <i>Hao Lee</i></p>	<p>8:00 AM CC1, Dislocations in AlGaInN-Based Laser Diodes <i>Tomonori Hino</i></p>	<p>8:00 AM *DD1, Lithographically-Induced Self-Assembly (LISA) of Nanostructures <i>Stephen Y. Chou</i></p>
<p>10:40 AM BB2, Optical, Structural, and Electrical Properties of Close-Packed Arrays of InP Quantum Dots <i>Olga I. Micic</i></p>	<p>8:20 AM CC2, Enhanced Light Emission from Strain-Tuned Modulation-Doped Quaternary AlInGaN/InGaN Quantum Wells <i>J. Zhang</i></p>	<p>8:40 AM DD2, Coulomb Crystals—A New Nanoscale Self Assembly Technique with Rapid Throughput <i>Supriyo Bandyopadhyay</i></p>
<p>11:00 AM +BB3, Electronic Structure Of Self-Limited InAs/GaAs Quantum Dots Grown Via Punctuated Island Growth Approach <i>Ildar Mukhametzhonov</i></p>	<p>8:40 AM +CC3, High Performance AlGaIn and GaN Photodetectors Grown by Metalorganic Chemical Vapor Deposition <i>Damien J. H. Lambert</i></p>	<p>9:00 AM DD3, Nanostructure Fabrication by Charged Clusters <i>Nong-Moon Hwang</i></p>
<p>11:20 AM +BB4, Evolution and Dissociation of InAs/InP Quantum Dots during Growth Interruption <i>Sukho Yoon</i></p>	<p>9:00 AM +CC4, UV Digital Cameras Based on 32x32 and 128x128 Arrays of AlGaIn p-i-n Photodiodes <i>J. D. Brown</i></p>	<p>9:20 AM +DD4, Electron Beam Induced Site-Control of Self-Assembled InAs Quantum Dots on InP Surfaces <i>Magnus Borgström</i></p>
<p>11:40 AM +BB5, Growth and Characterization of InP Self-Assembled Quantum Dots on GaAs Substrates <i>Jae-Hyun Ryou</i></p>	<p>9:20 AM +CC5, Growth and Characterization of High Quality Undoped and Si-Doped MBE AlN and Al_xGa_{1-x}N Layers <i>L. Kirste</i></p>	<p>9:40 AM Break</p> <p>10:20 AM +DD5, Dense Arrays of GaAs/InGaAs Nanostructures by Selective Area Growth Using Block Copolymer Lithography <i>Ruijuan Rian Li</i></p>
	<p>9:40 AM Break</p> <p>10:20 AM CC6, Upconversion Luminescence from FIB Er-Implanted GaN Films <i>Liang Chiun Chao</i></p>	<p>10:40 AM DD6, A New Quantum Structure Nano-Octahedra of MoX₂, X=S,Se <i>Philip A. Parilla</i></p>
	<p>10:40 AM +CC7, Nitride Semiconductors for Direct Photoelectrolysis of Water using Solar Energy <i>Joseph D. Beach</i></p>	<p>11:00 AM DD7, A Simple Purification of Single-Walled Carbon Nanotube Materials <i>Anne Catherine Dillon</i></p>
	<p>11:00 AM CC8, Late News</p> <p>11:20 AM CC9, Late News</p>	<p>11:20 AM DD8, Well-Aligned Carbon Nanotube Array Membrane Synthesized in Porous Alumina Template by Chemical Vapor Deposition <i>Hu-lin Li</i></p>
		<p>11:40 AM DD9, Late News</p>

2000 EMC At-A-Glance

Friday Morning, June 23, 2000

<p>Session EE. Non-Destructive Testing and In-Situ Monitoring/ Control</p>	<p>Session FF. Materials Integration: Wafer Bonding and Alternate Substrates</p>	<p><i>Friday Afternoon</i> Session GG. Characterization of Quantum Dots</p>
<p>8:00 AM EE1, Near-Field Surface Photovoltage <i>Yossi Rosenwaks</i></p> <p>8:20 AM +EE2, Surface Photovoltage Spectroscopy, Photoreflectance, and Reflectivity Characterization of an InGaAs/GaAs/GaAlAs Vertical-Cavity Surface-Emitting Laser Including Temperature Dependence<i>Y. S. Huang</i></p> <p>8:40 AM EE3, Characterization of GaAlAs/GaAs Heterojunction Bipolar Transistor Structures using Surface Photovoltage Spectroscopy<i>Fred H. Pollak</i></p> <p>9:00 AM +EE4, Photoreflectance Characterization of an AlInAs/GaInAs (Lattice-Matched to InP) Heterojunction Bipolar Transistor Structure with a Chirped Superlattice<i>L. Mourokh</i></p> <p>9:20 AM EE5, The Optical Constants of n-Doped InGaAs/InP (001) Including Moss-Burstein Shift Experiment and Modeling<i>M. Munoz</i></p> <p>9:40 AM Break</p> <p>10:20 AM EE6, In Situ and Ex Situ Spectroscopic Ellipsometry of Low-Temperature-Grown GaAs<i>Donald A. Gajewski</i></p> <p>10:40 AM +EE7, Real-Time Feedback Control of CF4 Plasma Etching Based on In-Situ Spectroscopic Ellipsometry<i>Tyler D. Parent</i></p> <p>11:00 AM +EE8, Combined BEMA-Beckmann and Kirchoff Approach to Modeling Polysilicon for In Situ Two-Channel Spectroscopic Reflectometry RIE Measurements<i>Brooke S. Stutzman</i></p> <p>11:20 AM EE9, Characterization of Compound Semiconductor Structures from X-Ray Diffraction Data by the Application of a Genetic Algorithm<i>M. Wormington</i></p> <p>11:40 AM EE10, Late News</p>	<p>8:00 AM +FF1, Relaxation of Si_{0.82}Ge_{0.18} Films Grown on Ultra-Thin Silicon on Insulator Substrates<i>E. M. Rehder</i></p> <p>8:20 AM +FF2, SiGe on Insulator Fabricated by Wafer Bonding and Etch-back<i>Gianni Taraschi</i></p> <p>8:40 AM +FF3, High-Dose Hydrogen Implantation in GaSb for Ion-Cut Bond and Transfer Applications<i>Y. Zheng</i></p> <p>9:00 AM +FF4, Wafer Fusion of GaAs/GaN Heterostructures<i>S. E. Monteith</i></p> <p>9:20 AM FF5, Defects at Bonding Interfaces and Compliant Substrates<i>P. Kopperschmidt</i></p> <p>9:40 AM Break</p> <p>10:20 AM +FF6, An Approach for Heterogeneous Integration of High Performance III-V Devices onto Silicon Using Field-Assisted Assembly<i>Christopher D. Nordquist</i></p> <p>10:40 AM +FF7, Strain Relaxation of InGaAs/AlAs/GaAs by Lateral Oxidation<i>Sheila K. Mathis-Yu</i></p>	<p>1:20 PM GG1, Shape Engineering to Improve the Threshold Temperature Dependence in Quantum Dot Lasers<i>Oleg B. Shchekin</i></p> <p>1:40 PM +GG2, Lasing from InAs Quantum Dots Embedded in GaAs Microdisk<i>L. Zhang</i></p> <p>2:00 PM +GG3, Time-Resolved Micro-Photoluminescence from Single CdSe Quantum Dots<i>Takeshi Ota</i></p> <p>2:20 PM GG4, Exciton Magnetic Polarons in a Single Diluted Magnetic Semiconductor Quantum Dots<i>M. Welsch</i></p> <p>2:40 PM GG5, Charge Carrier Cooling in InP Quantum Dots: Visible and Infrared Transient Absorption Studies<i>Randy J. Ellingson</i></p> <p>3:00 PM Break</p> <p>3:40 PM +GG6, Photoluminescence of InAs Quantum Dots near a Two-dimensional Electron Gas<i>Y. H. Luo</i></p> <p>4:00 PM GG7, Anti-Stokes Photoluminescence in Colloidal Semiconductor Quantum Dots<i>Don Selmarten</i></p> <p>4:20 PM +GG8, Spontaneous Far Infrared Emission from Self Organized In_{0.4}Ga_{0.6}As/GaAs Quantum Dots<i>Sanjay Krishna</i></p> <p>4:40 PM GG9, Conductance Spectroscopy on InAs Quantum Dot Ensemble<i>Kanji Yoh</i></p>

2000 EMC At-A-Glance

Friday Morning, June 23, 2000

<p align="center">Session HH. Dopant and Other Point Defects in Wide Bandgap Semiconductors</p>	<p align="center">Session II. Nanostructure Fabrication - II</p>	<p align="center">Session JJ. Device Processing: Etching, Implantation, Oxidation and Passivation</p>
<p>1:20 PM +HH1, Inhomogeneous Indium Incorporation in InGaN(0001) Surfaces <i>Huajie Chen</i></p>	<p>1:20 PM +II1, Semiconductor Nanostructure Formation Using Dip-Pen Nanolithography <i>A. J. Blattner</i></p>	<p>1:20 PM +JJ1, Low Damage and Selective Etching GaN over AlGaN for Gate-Recessing of AlGaN/GaN HFETs <i>William B. Lanford</i></p>
<p>1:40 PM +HH2, Growth Characterization and Optimization of Mg-doped GaN <i>Gon Namkoong</i></p>	<p>1:40 PM +II2, Self Alignment of Patterned Substrates using Hydrophobic/Hydrophilic Interactions <i>Donna C. Furnanage</i></p>	<p>1:40 PM +JJ2, Chemically Assisted Ion Beam Etching of GaN-Based Waveguides and Photodectors <i>Arkadi Goulakov</i></p>
<p>2:00 PM HH3, Mg Doping—An Example of Classic Surface Accumulation/Segregation During Doping <i>Thomas H. Myers</i></p>	<p>2:00 PM II3, AFM Nanolithography for Selective Growth of High-Density Array of ZnCdS/ZnMgCdS Quantum Dots <i>Adrian Avramescu</i></p>	<p>2:00 PM +JJ3, Photoelectrochemical Selective Etching of AlGaN/GaN Device Structures <i>Ting Gang Zhu</i></p>
<p>2:20 PM +HH4, Magnesium Memory Effects in AlGaN/GaN HBTs Grown by Metalorganic Chemical Vapor Deposition <i>Damien J. H. Lambert</i></p>	<p>2:20 PM +II4, Fabrication of Nanometer-Scale InAs Quantum Structures by Electron-Beam Lithography and Reactive Ion Etching <i>Andy Cheng</i></p>	<p>2:20 PM +JJ4, Index Guided II-VI Lasers with Low Threshold Current Densities <i>Matthias Strassburg</i></p>
<p>2:40 PM +HH5, Investigation of P-Type GaN Co-Doped with Oxygen <i>Roman Y. Korotkov</i></p>	<p>2:40 PM II5, InAs Dots Grown by MBE on InAlAs and InGaAs Lattice Mismatched Buffers on GaAs <i>Yvon Cordier</i></p>	<p>2:40 PM +JJ5, Comparative Studies of Thermal Oxidation of Sacrificial Silicon on 4H-SiC Epilayer <i>Adrian C. H. Koh</i></p>
<p>3:00 Break</p>		<p>3:00 PM Break</p>
<p>3:40 PM HH6, Co-Implantation Studies in GaN <i>Brian J. Skromme</i></p>		<p>3:40 PM +JJ6, Use of Dual Sided Controlled Oxidation to Produce Ultra Thin Silicon on Insulator or Silicon on Air Membranes Formed by Epitaxy Techniques <i>Steve Bourland</i></p>
<p>4:00 PM +HH7, Optically and Thermally Detected Deep Levels IN n-GaN: Effect of Hydrogenation <i>Adrian Hierro</i></p>		<p>4:00 PM JJ7, Characterization of UV-Ozone Oxidized InGaAs/InP Heterostructures <i>R. Driad</i></p>
<p>4:20 PM HH8, Electron Beam Induced Increase of Electron Diffusion Length in p-type GaN and AlGaN/GaN Superlattices <i>Leonid Chernyak</i></p>		<p>4:20 PM +JJ8, Fabrication of InP Metal-Insulator-Semiconductor Structures Using BaTiO₃ as an Insulating Layer <i>R. R. Sumathi</i></p>
<p>4:40 PM HH9, Cross Sectional Scanning Probe Studies of Hydride Vapor Phase Epitaxy GaN Films <i>Julia W. P. Hsu</i></p>		<p>4:40 PM JJ9, Investigations on the Proton Irradiation Induced Defects on Ni/n-GaAs Schottky Barrier Diodes <i>P. Jayavel</i></p>
<p>5:00 PM HH10, Real Time Observations of the Formation of Nanopipes in GaN <i>Eric A. Stach</i></p>		

2000 Electronics Materials Conference Grid

WEDNESDAY, JUNE 21ST

THURSDAY, JUNE 22ND

FRIDAY, JUNE 23RD

AM

PM

AM

PM

AM

PM

REGISTRATION

EXHIBITS

3:00PM-8:00PM, Tuesday, June 20, 2000, Driscoll Center North, Flounders Lounge
 7:00AM-5:00PM, Wednesday, June 21, 2000, Driscoll Center North, Flounders Lounge
 7:00AM-4:00PM, Thursday, June 22, 2000, Driscoll Center North, Flounders Lounge
 7:00AM-10:00AM, Friday, June 22, 2000, Driscoll Center North, Flounders Lounge

9:20AM-5:00PM & 7:00PM-9:00PM,
 Wednesday, June 21, 2000, Driscoll
 Center North, Ballroom C/D
 10:00AM-4:00PM, Thursday, June 22, 2000,
 Driscoll Center North, Ballroom C/D

Sturm Hall- Sturm Auditorium	EMC Plenary Lecture/Student Awards		Session P. Transport Properties in Nitride Structures	Session V. Point and Extended Defects in Mis- matched Materials	Session CC. Nitride Optoelectronics	Session HH. Dopant and Other Point Defects in Wide Bandgap Semiconductors
Johnson-McFar- lane Cafeteria	Session A. Mid-IR Devices - I	Session G. Mid-IR Devices - II				
Centennial Towers Lounge	Session B. Modeling of Nanostructures	Session H. Special Topical Session				
Sturm Hall-Lindsey Auditorium	Session C. Polarization and Piezoelectric Effects in Nitrides	Session I. Advanced Nitride Epitaxy	Session O. Nanometer Scale Characterization	Session U. Properties of Quantum Wires and Wells, Wires, Superlattices	Session AA. Novel Materials Session BB. Advances in the Growth of Quantum Dots	Session GG. Characterization of Quantum Dots
Centennial Halls Cafeteria	Session D. Photonic Bandgap Materials	Session L. Organic TFT's and Electronic Transport	Session R. Silicon Integration: Thin Oxides, Alternate Dielectrics and Epitaxial Metals	Session X. Silicon Integration Issues: Metallization and Low-K Dielectrics	Session EE. Non-Destructive Testing and In-Situ Monitoring/Control	Session JJ. Device Processing: Etching, Implan- tation, Oxidation and Passivation
Driscoll Center North - Pub	Session E. Organic Materials and Devices - I	Session J. Contacts to GaN and Other Wide Bandgap Semiconductors	Session Q. SiC Contacts and Ion Implantation	Session W. SiC Growth and Device Processing	Session DD. Nanostructure Fabrication - I	Session II. Nanostructure Fabrication - II
Centennial Halls Main Lounge	Session F. Oxides of Compound Semiconductors	Session M. Transparent Con- ducting Oxides - I: Materials and Defects Physics	Session S. Transparent Conducting Oxides II - Films	Session Y. Organic Materials and Devices - II	Session FF. Materials Integration: Wafer Bonding and Alternate Substrates	
Sturm Hall Main Room: 186, Satellite Rooms: 253-254		Session K. Si-Based Heterostructures				
Driscoll Center N. - Ballroom A/B			Session N. Epitaxy for Devices	Session T. InGaAsN and Related Materials	Session Z. Ordering in Semiconductor Alloys	

2000 Electronic Materials Conference

TECHNICAL PROGRAM

University of Denver · Denver, Colorado · June 21 - 23, 2000

* Indicates Invited Paper

+ Indicates Student Paper

Wednesday, June 21, 2000

EMC PLENARY LECTURE/STUDENT AWARDS/Gregory Stillman Award

Ceremony: 8:20 AM

Room: Sturm Auditorium

Session Chairman: M. R. Melloch, Purdue University, School of Electrical and Computer Engineering, West Lafayette, IN 47907 USA

Plenary Speaker: L. L. Kazmerski

Topic: Photovoltaics Research and Development: A Tour Through the 21st Century: L. L. Kazmerski¹; ¹National Renewable Energy Laboratory, 1617 Cole Boulevard, MS 3221, Golden, CO 80401 USA

BREAK: 9:20 AM-10:00 AM

Session A. MID-IR Devices - I

Wednesday AM Room: Johnson-McFarlane
June 21, 2000 Cafeteria

Session Chairs: Ralph Dawson, University of New Mexico, Albuquerque, NM USA; Andrew Johnson, DERA, Great Malvern, UK

10:00 AM, A1

The Effect of Different Interfaces on MOCVD III/AsSb Optical Properties and Device Performance: R. M. Biefeld¹; S. R. Kurtz¹; M. R. Pillai²; S. A. Barnett²; ¹Sandia National Laboratories, Dept. 1113, MS0601, P.O. Box 5800, Albuquerque, NM 87185-0601 USA; ²Northwestern University, Dept. Matls. Sci. and Eng., Evanston, IL 60208 USA

The group III arsenide-antimonide compound semiconductors are becoming increasingly important in a number of technological applications. These applications include infrared lasers and detectors, high speed oscillators, and tunnel junction structures. Interfacial properties are important in all of these applications. Previous work has shown the importance of controlling the composition at the interfaces in these structures as well as the existence of a segregated Sb layer on the growth surface for the InAs-GaSb, GaAsSb-GaAs, and InAsSb-InAs heterojunctions. In this paper we will report on our recent characterization of metal-organic chemical vapor deposition (MOCVD) grown III-AsSb superlattices and epitaxial layers using x-ray diffraction, photoluminescence, AFM, and device characterization. We have correlated the effects of interface changes with the properties of InAsSb/InAs multiple quantum wells, InAsSb/InPSb super-lattices and lasers, and InGaAsSb layers. The optical properties of InAsSb/InPSb superlattices revealed an anomalous low energy transition that can be assigned to an antimony-rich, interfacial

layer. This low energy transition can be eliminated by introducing a 1.0nm InAs layer between the InAsSb and InPSb layers in the superlattice. An InAsSb/InAs/InPSb/InAs SLS laser yielded improved lasing threshold and temperature characteristics when the InAs layer was added to the superlattice. During the growth of InAsSb/InAs (001) multi-quantum wells using metal-organic chemical vapor deposition, kinematical x-ray diffraction modeling indicates that Sb segregates to the surface with an estimated segregation length of 1 to 2 nm. Up to ~ 0.8 ML of Sb floats on the surface during the growth of these structures. Lowering the growth temperature or increasing the growth rates lead to sharper interfaces, but in some cases this also reduces photoluminescence intensity. Using arsine purging both prior to and after the InAsSb layer growth sharpens the InAs/InAsSb interfaces, leading to more intense PL peaks. During the growth of InGaAsSb the surface degrades if the reactants are simply turned off. The resulting layers have very weak photoluminescence. We have used a capping GaSb layer to prevent this degradation and to improve the photoluminescence by over an order of magnitude. Improved optical properties and laser performance has resulted from the optimization of interfaces in these materials. We will present the techniques used to optimize the optical properties of these materials and also discuss the performance characteristics of devices made from these materials.

10:20 AM, A2

High Efficiency 4.4 μm Type-II Interband Cascade Laser: Stefan John Murry¹; Sergey V. Zaitzev¹; Wen-Yen Hwang¹; Chih-Hsiang Lin¹; Jae-Yoon Um¹; Al Delaney¹; ¹Applied Optoelectronics, Inc., 4800 Calhoun, SR1 Rm. 724, Houston, TX 77204-5507 USA

High-performance interband cascade lasers have been fabricated with an emission wavelength of 4.42 μm at 80K operating temperature. The devices demonstrated a peak output power in pulsed mode (5 μs pulse length and 1 kHz repetition rate) of 200 mW per (uncoated) facet. Under these pulse conditions, an average external quantum efficiency (EQE) of 580% was measured, for a device with a cavity length of 850 μm . To our knowledge, this is the highest EQE ever reported for an interband cascade laser. The threshold current density for this device is only 23.5 A/cm², and increasing the operating temperature to 140K results in a threshold current density of only 100 A/cm². The devices were operated in continuous wave (cw) mode, where an output power of 53 mW per facet is obtained at 80K. This output power is achievable with an injection current of only 250 mA. Threshold current density in cw mode is 35 A/cm² with an applied bias of 6.3 V, and the EQE is 193%. Continuous wave operation is observed up to 120K. The device structure was grown by molecular beam epitaxy (MBE), and consisted of 20 stages of active regions, separated by injection regions that serve to collect carriers from one quantum well (QW) region and inject it into the appropriate energy level in the next QW region. The QW regions are similar to the "W" structure first proposed by Meyer, et al. [1]. Each "W" region is composed of a multiple QW region containing 24.9 \AA InAs/39.5 \AA InGaSb/21.5 \AA InAs/17.3 \AA AlSb/41.8 \AA InGaSb/17.3 \AA AlSb/50.8 \AA GaSb/13.8 \AA AlSb. The lasers were processed using a mesa structure for current confinement. Testing of various etch depths confirmed the necessity for a mesa structure, as lasers with deep mesa etching show a lower threshold current density and higher EQE than shallow etched mesas of the same width. This is due to strong lateral current spreading in the active region. This lateral current spreading is confirmed by imaging the luminescence of the facet below threshold, where luminescence can be seen to extend far outside the region defined by the electrical contacts. This is expected, since the active region contains a large number of quantum wells, which have relatively poor vertical electrical conductivity, but good lateral conductivity. The deep etching and other improvements in the processing and packaging are believed to be the primary contributors to the

improved performance relative to previous devices measured by the authors. It is expected that future devices will also benefit from these improvements. [1]C. L. Felix, W. W. Bewley, I. Vurgaftman, J. R. Meyer, D. Zhang, C.-H. Lin, R. Q. Yang, and S. S. Pei, "Interband cascade laser emitting > 1 photon per injected electron," IEEE Photon. Tech. Lett., 9, pp. 1433-35 (1997).

10:40 AM, A3

Optical Characterization and Determination of the Band Discontinuity of the Type-II GaAsSb/InGaAs W Structure QWs: *Sang-Wan Ryu*¹; Paul Daniel Dapkus¹; ¹University of Southern California, Depts. of Elect. Eng./Electrophys., University Park SSC 502, Los Angeles, CA 90089 USA

Vertical Cavity surface emitting lasers (VCSELs) operating at 1.3 micrometer have gained considerable interest for optical communication systems and data links. It is expected that VCSELs grown on GaAs substrates have significant advantages because they are compatible with well developed GaAs/AlAs distributed Bragg reflectors and AlAs oxidation techniques. However, it is not easy to find materials to be grown on GaAs substrates with bandgaps that are suitable for 1.3 micrometer emission. Several materials, such as GaInNAs quantum wells (QW), GaAsSb QW, and InGaAs quantum dots, have been studied, but none of them have been successful to realize a 1.3 micrometer VCSEL. A type-II structure has the advantage that its transition energy is determined by structural design not by solely by the bandgap of each material. Such structures have been used successfully to fabricate infrared photodetectors and diode lasers. GaAsSb/InGaAs heterojunctions on GaAs substrates are expected to show 1.3 micrometer luminescence, so their optical characterization is studied in this work. The band alignment of the constituent layers is an important parameter to determine the transition energy of type-II structure. We measured the conduction band discontinuity by fitting experimental optical transition energies with different structures. All samples were grown by low pressure metal organic vapor phase deposition at 600°C. The undoped In_{0.19}Ga_{0.81}As/GaAs_{0.73}Sb_{0.27}/In_{0.19}Ga_{0.81}As W structures with various thicknesses were sandwiched by AlGaAs cladding layers. Their band-to-band transitions were measured by photoluminescence at room temperature. Three samples with different InGaAs thickness were grown and their transition energies were measured. To determine the band offset, we calculated QW transition energy with band parameters taken from literature except for the conduction band discontinuity (ΔE_c) of In_{0.19}Ga_{0.81}As/GaAs_{0.73}Sb_{0.27} which was taken as a fitting parameter. Good agreement is obtained between the measured and calculated peak energies when including the effect of strain and using a ΔE_c of -210 meV. Negative value means type-II band alignment, i.e. conduction band of GaAsSb is higher than that of InGaAs. Based on this value, the wavefunction overlap between electron and hole, separation of transition energy between ground and first excited transitions were calculated. In addition, we found that reduction of GaAsSb thickness with the increase of the InGaAs thickness is an efficient way to increase the transition wavelength without the accumulation of excessive strain. As a result, we can get strong photoluminescence at 1.3 micrometer with a GaAsSb/InGaAs W structure on a GaAs substrate.

11:00 AM, A4

Near-Diffraction-Limited Angled-Grating Distributed Feedback Type-II "W" Laser at 3.3 Microns: *Robert Ernest Bartolo*¹; William W. Bewley¹; Igor Vurgaftman¹; Jerry R. Meyer¹; M. J. Yang¹; ¹Naval Research Laboratory, Optical Sci.-Code 5613, 4555 Overlook Ave. SW, Washington, DC 20375-5338 USA

We report on the fabrication and testing of an angled-grating distributed feedback (or alpha-DFB) quantum well laser emitting near 3.3 microns. The 1.9-micron-period grating patterned at a 16° angle relative to the facet normal was defined by a photoresist etch mask using i-line projection lithography. A combination of dry and wet etching produced a relatively vertical etch profile and uniform etch depth. The epitaxial structure with a type-II antimonide "W" active region was grown by MBE. For pulsed optical pumping at T=78K, with a stripe width of 50 microns, the lateral (slow-axis) far-field profile had a single lobe with a near-diffraction-limited divergence angle of 1.4° FWHM. A Fabry-Perot device occupying an adjacent unpatterned portion of the same laser bar had the typical doubled-lobed profile with a divergence angle of 23°. The threshold of the alpha-DFB laser was slightly lower, and the external efficiency was 64% of that for the Fabry-Perot device. With increasing

pump-stripe width, the alpha-DFB divergence angle increased somewhat, but the far field remained roughly gaussian and single-lobed to a width of at least 800 microns.

11:20 AM, A5

Lead Salt Based Vertical Cavity Surface Emitting Lasers for the 4-6 Micron Wavelength Range: *Thomas Schwarzl*¹; Wolfgang Heiss¹; Gunther Springholz¹; Michael Aigle²; Harald Pascher²; ¹Universitaet Linz Institut für Halbleiterphysik, Abteilung für Festkörperphysik, Altenbergerstrasse 69, Linz A-4040 Austria; ²Universität Bayreuth, Experimentalphysik I, Universitätsstr. 30, Bayreuth D-95447 Germany

Coherent emitters for the mid infrared (MIR) range are of high interest due to various gas absorption lines in this region permitting sensitive gas spectroscopy. For these applications usually semiconductor lasers made from lead salts (IV-VI) compounds are used. Although in recent years much progress has been achieved with MIR III-V quantum cascade lasers and with type II antimony based lasers, the lead salt lasers still represent the highest cw operation temperature for electrically pumped MIR diode lasers. In the present work, IV-VI vertical cavity surface emitting lasers (VCSELs) for the 4-6 μm range are demonstrated. This represents the longest wavelengths for VCSELs up to now. In VCSELs, some major advantages over conventional edge emitters, such as circular beams with very low beam divergence or simplified fabrication of high power laser arrays, are gained. Up to now, VCSELs have been fabricated only from III-V and II-VI semiconductors mostly for the visible and near infrared range with the longest MIR wavelength at 3 μm . Our IV-VI VCSEL samples were grown by molecular beam epitaxy and consist of two distributed Bragg reflectors (DBRs) with $\lambda/2$ or 2λ microcavities in-between. PbTe quantum wells (QWs) at the antinode positions of the cavity standing wave are intended as laser active layers. The multilayer structures were designed using the transfer matrix method and a model for the dielectric function of the lead salts. The DBRs consisted of Pb_{0.95}Eu_{0.05}Te and EuTe $\lambda/4$ layer pairs. Due to the very high refractive index contrast of over 80% between these mirror materials, only three layer pairs are required to obtain reflectivities in excess of 98%. The VCSELs were optically pumped with pulsed laser excitation. Strongly forward directed stimulated emission was found at 6.07 μm for sample 1 below 25K with a line width of 11 nm (370 meV). Sample 2 emitted at 4.82 μm between 35K and 85K with a line width of only 4 nm (210 meV). The line widths linearly decrease with increasing pump power, as expected for laser emission. Both emission wavelengths agree with microcavity resonances and pronounced spectral narrowing with respect to the corresponding resonances is observed. Comparison of the cavity mode positions with envelope function calculations of the QW energy levels indicate lasing occurs due to transitions between the ground level of the oblique valleys in the conduction and valence bands. Furthermore, we found clear indications that the maximum operation temperature of our VCSELs is not due to intrinsic effects but is only determined by the cavity design. Our experimental results demonstrate the feasibility of IV-VI VCSELs and thus represent an important prerequisite for electrically pumped MIR VCSELs.

11:40 AM, A6

Controlled Precipitation and Formation of Self-Aligned Quantum-Dot Arrays in Quasi-Binary Semiconductor Alloys: *Choong-Un Kim*¹; Manjong Lee¹; ¹The University of Texas at Arlington, Matls. Sci. and Eng. Dept., Arlington, TX 76006 USA

Assembling a dense array of semiconductor quantum dots of uniform size and distribution is key to the success of quantum dot technology and has been a subject of intense research for some time. While several methods have been introduced in recent years to realize such a structure, their application is limited to a small group of materials. In addition, these methods, largely based on the epitaxial thin film processes, generally lack simplicity and flexibility both in material selection and processing conditions. In our recent attempts, we discovered that controlled precipitation induced in multi-phase semiconductor alloys can be a simple, yet, effective technique for producing a highly organized array of quantum dots that are even lattice-matched to the matrix. Controlled precipitation as a way to form nano-size particles is not a new concept. It has been utilized extensively in metal alloys for the past 60 years. Controlled precipitation in metal alloys essentially consists of a three-step heat treatment: solid-solution treatment, quenching and aging. When a small amount of a solute element is added to a pure metal to form a solid solution at high temperature, rapid cooling forces the structure to remain in the single-phase state even when there is less solubility at low tempera-

tures. The alloy is then aged at a relatively low temperature to induce homogeneous nucleation and growth of precipitates. Evidence that controlled precipitation can be equally effective for semiconductors is presented in this paper using the PbTe-HgTe quasi-binary alloy system. In our alloy system, PbTe was chosen for the matrix phase with HgTe as the precipitate phase. (Since the band-gap of PbTe (~0.3 eV) is considerably larger than that of HgTe (~0 eV), a nano-sized HgTe precipitate is expected to act as a quantum dot.) A small amount of HgTe (4-mol%) was added to a PbTe ingot and heat-treated at 600°C for several days to form a solid solution. The alloy was then air-cooled to room temperature, followed by aging at 300°C and 400°C for various times, ranging from 1 hour to 400 hours. TEM and x-ray characterization of the alloy revealed that the precipitation was complete within an hour of aging and resulted in extremely dense array of HgTe square-plates less than 10 nm wide and a few nm thick. In addition, these plates are aligned with the {100} planes of the PbTe matrix and have a coherent interface, which is essentially the same structure as the HgTe epi-layer grown on PbTe {100} surface. These plates also showed exceptional thermal stability because their size and shape did not change with further aging. Precipitates, their growth mechanism and exceptional stability, will be discussed in detail along with experimental results.

Session B. Modeling of Nano-Structures

Wednesday AM Room: Centennial Towers
June 21, 2000 Lounge

Session Chairs: Supriyo Bandyopadhyay, University of Nebraska, Dept. of Elect. Eng., Lincoln, NE 68588-0511 USA; Michael Flatte, University of Iowa, Dept. of Phys., Iowa City, IA 52252 USA

10:00 AM, B1 *Invited

Modeling of Nanotube Devices: *Francois Leonard*¹; Jerry Tersoff¹; IBM, T.J. Watson Rsch. Ctr., P.O. Box 318, Yorktown Heights, NY USA

Carbon nanotubes hold great promise for nanoscale devices. However, theoretical modeling shows that they behave very differently from traditional devices, largely due to the quasi-one-dimensional geometry. This presents both problems and opportunities, as illustrated by calculations of doping and depletion, Schottky barriers, and quantum transport.

10:30 AM, B2 *Invited

Modeling of Transport in Carbon Nanotube Wires: *M. P. Anantram*¹; ¹NASA Ames Research Center, Moffett Field, CA 94035-1000 USA

Carbon nanotubes have emerged as a promising material for many applications in molecular electronics such as wires, field emitters and sensors. A typical nanotube sample is however not well characterized at the atomic level, and there can be substantial variation from sample to sample. This makes atomic scale modeling a valuable tool to understand the role of various processes such as defect scattering, nanotube-metal coupling, and applied voltage, in determining the measured electronic properties. In this talk, we focus on atomic scale modeling of electron flow through carbon nanotube based wires. Carbon nanotubes have a unique band structure. As a result, at small applied biases, only the crossing subbands contribute to current flow. The large velocity associated with these subbands and the lack of states to scatter into play an important role in determining the large conductances measure in nanotubes. At large applied biases (where electrons are injected into many subbands), our modeling studies show that the conductance is not commensurate with the large number of subbands. For example, at an applied bias of 2.5V, electrons are injected into twenty subbands, in a (20,20) nanotube. We, however find that the differential conductance is only comparable to $4e^2/h$. We show that this arises because Bragg reflection plays an important role in determining the conductance of nanotube wires, at large applied biases. The subband spacing decreases with increase in nanotube diameter. As a result, Bragg reflection is weakened because Zener tunneling becomes important with decrease in subband energy level spacing.

Finally, we simulate the role of defect scattering in determining both the role of small and large bias conductance. It is shown that transport through the crossing subbands at small biases is not significantly affected by defect scattering. However, defect scattering can increase the differential conductance at large applied biases due to inter-subband scattering.

11:00 AM, B3 +

Self-Consistent Green's Function Theory for Molecular Electronic Devices: *Yongqiang Xue*¹; Supriyo Datta¹; ¹Purdue University, Sch. of Elect. and Comp. Eng. Depts., 1285 EE Bldg., West Lafayette, IN 47906 USA

There is currently a great deal of interest in modeling molecular electronic devices consisting of short molecules sandwiched between two metallic contacts. Such metal-molecule interfaces require a hybrid model that combines the quantum chemistry of isolated molecules with the surface physics of metallic substrates. However, the perturbation due to the coupling at the interface extends over only a finite region due to the metallic screening in the electrodes. The Green's function theory, combined with the first-principles real-space description of the electronic structure, provides a powerful framework which takes full advantage of this spatial locality while maintaining the simple physical picture of bonding in molecules. In this work, we show how molecular electronic devices can be modeled quantitatively using the density-functional theory within the local-spin-density approximation and the linear-combination of Gaussian-type orbital approach. Topics discussed include the interfacial charge transfer, band line-up and the low bias conductance.

11:20 AM, B4

Atomistic Simulation of Quantum Dots Including Strain and Bandstructure: *Gerhard Klimeck*¹; R. Chris Bowen¹; Timothy B. Boykin²; ¹Jet Propulsion Laboratory, California Instit. of Tech., MS 168-522, 4800 Oak Grove Dr., Pasadena, CA 91109 USA; ²The University of Alabama- Huntsville, Dept. of Elect. Eng., Huntsville, AL 35899 USA

As microelectronic research moves devices to nanometer scale operating at GHz speeds, the physics of electron flow through devices becomes more complicated and physical effects, which previously could be ignored safely in microelectronic devices, become significant. High energy electron injection, quantization of charge, quantization of energy, and electron scattering interactions are some of the phenomena that are presently being investigated experimentally and theoretically. Raytheon/TI developed a 1-D quantum device simulator (NEMO-1D) to address such issues. That effort combined expertise in device physics, numerical and graphical user interface technologies to produce the first quantitative, general-purpose quantum device simulator. A similarly versatile, quantum mechanics-based, 3-D simulation tool does not exist. The work presented here is an extension of the of the NEMO 1-D software to 3-D modeling to enable quantum dot simulations of electronic structures and optical interactions. NASA's interest in long wavelength infrared imaging and the advancements of computation technology has sparked research in quantum dots at JPL. Near term interest in self-assembled InAs quantum dots on GaAs substrates lies in far-infrared detectors with reduced dark current, increased temperature of operation, increased radiation hardness, and increased sensitivity over quantum well infrared detectors. Since the InAs quantum dots are highly strained in the GaAs matrix it is essential to model the effects of this strain on the electronic structure. We implemented a nearest neighbor tight binding model including s, p and d orbitals that can model conduction and valence bands throughout the Brillouin zone. This model, unlike the second-nearest neighbor sp^3s^* , can easily include effects due to stress and strain, since it is only based on two-center integrals. The interaction energies in this model are fit to experimentally observed quantities such as bandgaps, effective masses, and strain induced shifts using a genetic algorithm. The mechanical strain in the quantum dots is computed via conjugate gradient-based minimization using the Keating potential. Resonance states are computed using a customized parallel Lanczos eigenvalue solver for systems of about one million atoms. This presentation will show our recent electronic structure analysis InAs/GaAs systems.

11:40 AM, B5

Pseudopotential Calculations of Addition Energies and Optical Transitions in Charged InAs and CdSe Quantum Dots: *Alberto Franceschetti*¹; Alex Zunger¹; ¹National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

Recent single-dot STM experiments [U. Banin et al., Nature 400, 542 (1999)] have allowed for the first time the observation of atomic-like electronic states in strongly-confined semiconductor quantum dots. The tunneling conductance shows, as a function of the applied voltage, a series of narrow peaks corresponding to the electron and hole charging energies. According to Keldish, the energy required to add an electron or a hole to a quantum dot can be manipulated by altering the dielectric constant of the surrounding environment. To quantify this effect, we have calculated the electron and hole charging energies of InAs and CdSe quantum dots as a function of the dielectric constant of the barrier material. Atomistic pseudopotential wave functions are used as input to the many-body expansion of the total energy of the charged dots, and surface-polarization effects due to the dielectric mismatch at the surface of the quantum dot are fully included in the calculation. We show how the addition energies, the quasi-particle gap, and the optical gap of the quantum dot depend on the dielectric constant of the surrounding material, and provide scaling laws for these quantities as a function of the dot size. Our results are in excellent agreement with STM experiments, and provide a microscopic interpretation of the measured addition energies. Future devices may depend on loading electrons or holes into quantum dots. We have thus calculated the emission and absorption spectra of charged CdSe quantum dots. We find that: (i) When a charge q is added to the quantum dot the emission and absorption lines are shifted in energy by an amount approximately proportional to q . This is a consequence of the different shape of the electron (e) and hole (h) wave functions, which results in the following sequence of Coulomb energies: $J_{hh} > J_{eh} > J_{ee}$. (ii) When $|q| > 2e$ new high-energy lines progressively appear in the emission spectrum due to state-filling effects and to the exchange interaction between spectator particles, while low-energy lines progressively disappear from the absorption spectrum as a result of "Pauli blockade" effects.

12:00 PM, B6 Late News

Session C. Polarization and Piezoelectric Effects in Nitrides

Wednesday AM Room: Lindsey Auditorium
June 21, 2000 Location: Sturm Hall

Session Chairs: James S. Speck, University of California-Santa Barbara, Matls. Dept., Santa Barbara, CA 93106 USA; Joan M. Redwing, Penn State University, Matls. Sci. and Eng. Dept., University Park, PA 16802 USA

10:00 AM, C1

MBE Growth and Characterization of AlGaIn/GaN Quantum Well Structures with Large Built-In Electric Fields: *H. M. Ng*¹; R. Harel¹; S.N.G. Chu¹; I. Brener¹; A.Y. Cho¹; ¹Bell Laboratories, Lucent Tech., 6H-424, 600 Mountain Ave., Murray Hill, NJ 07974 USA

Large built-in electric fields have been predicted in the hexagonal III-nitride materials due to spontaneous and piezoelectric polarization [1]. Several groups have studied the effects of these built-in fields on the optical properties of AlGaIn/GaN quantum wells [2,3]. The photoluminescence (PL) peak for wider quantum wells ($>30\text{\AA}$) has a large red-shift due to the quantum-confined Stark effect (QCSE). However, in those studies the AlN mole fraction of the AlGaIn barriers was varied only up to about 25%. It is of interest to investigate the magnitude of the built-in electric field with a systematic increase of the AlN mole fraction in the barrier layers and make comparisons to theoretical predictions as these fields play an important role for optical devices. In this work, AlGaIn/GaN single and multiple quantum well structures have been grown on (0001) sapphire substrates by molecular beam epitaxy. Transmission electron microscopy studies of the cross-section of these structures show that the interfaces between the well and barrier layers are abrupt with little interdiffusion. This is also evidenced by the observation of higher order superlattice peaks in the omega-2theta x-ray diffraction scans.

Several samples were grown with a number of single GaN quantum wells ranging from 10-40Å thick and the Al_x/Ga_{1-x}N barriers with $x=0.25$ to 0.80. The entire structure is grown on a thick (~0.6 micron) GaN buffer layer and therefore the AlGaIn barriers (60Å) are expected to be coherently strained to the GaN layer. Photoluminescence studies at low temperature (4K) show strong QCSE due to the large built-in electric field. For the sample with up to 80% AlN mole fraction in the barriers and a quantum well thickness of 30 and 40Å, the PL peaks occur at 460 and 505 nm respectively. This allows for the possibility of tuning the PL peak by varying only the thicknesses of the GaN quantum wells. Calculations using the envelope function approach were performed to estimate the magnitude of the electric field as a function of the AlN mole fraction in the barrier layers. [1] V. Fiorentini and F. Bernardini, Phys. Rev. B 60, 8849 (1999). [2] N. Grandjean, B. Damilano, S. Dalmaso, M. Leroux, M. Laugt, and J. Massies, J. Appl. Phys. 86, 3714 (1999). [3] R. Langer, J. Simon, V. Ortiz, N.T. Pelekanos, A. Barski, R. Andre, and M. Godlewski, Appl. Phys. Lett. 74, 3827 (1999).

10:20 AM, C2 +

Critical Layer Thickness Determination of GaN/InGaIn Single and Double Heterostructures: *Mason J. Reed*¹; Christopher A. Parker²; John C. Roberts²; Nadia A. El-Masry¹; Salah M. Bedair²; ¹NCSU, Matls. Sci. and Eng. Depts., 239 Riddick Labs., P.O. Box 7907, Raleigh, NC 27695-7907 USA; ²NCSU, Elect. and Comp. Eng. Depts., 232 Daniels, P.O. Box 7911, Raleigh, NC 27695-7911 USA

Light emitting devices in the nitride system are based mainly on the strained GaN/InGaIn/GaN double heterostructure. The thickness of the InGaIn wells used in these devices is assumed to be less than the thickness at which relaxation begins. However, there have not yet been any reported data about the critical layer thickness (CLT) in these double heterostructures. We will report on an approach to determine the variation of CLT in GaN/InGaIn single and double heterostructures in the composition range $0 < \% \text{InN} < 20$. The approach adopted to determine the value of CLT was to follow the evolution of the photoluminescence (PL) spectra as the InGaIn well or layer thickness was increased for a given %InN. We found that the emission energy from thin InGaIn wells/layers was higher than that of thick wells/layers due to compressive stress and possible quantum size effects. In the double heterostructures it was found that there was a sudden drop in the emission energy when the InGaIn well exceeded a given thickness. The change in emission energy is nearly a step-function at a given well width that we define as the critical layer thickness of the InGaIn film in the GaN/InGaIn/GaN double heterostructure. This is in contrast to the GaN/InGaIn single heterostructure, which we observed to exhibit a gradual relaxation process. It is also observed that the PL emission intensity and FWHM of the emission spectra can be correlated to the value of the CLT. Electrical measurements made on the single heterostructure layers also corroborate the PL data. For example, when the InGaIn film thickness was changed, there was a sudden change in the carrier concentration, mobility, and resistivity at the optically determined critical layer thickness of the InGaIn. In addition, we will report on the possible relaxation mechanisms of the InGaIn films and other electrical properties associated with the relaxation process.

10:40 AM, C3 +

Exploring the Effects Tensile and Compressive Strain on 2DEG Properties with the Aid of AlInGaIn Quaternary Alloys: *Steven Francis LeBoeuf*¹; Mike Aumer¹; Salah Bedair¹; ¹North Carolina State University, Elect. and Comp. Eng. Depts., Raleigh, NC 27695 USA

Because the lattice constant of InGaIn is inherently greater than that of GaN, GaN/InGaIn quantum wells are naturally subjected to compressive strain. It has thus been challenging to isolate the effects of strain-induced piezoelectric fields on 2DEG properties from other significant effects, such as conduction band offset and spontaneous polarization. But with the advent of high-quality AlInGaIn quaternary cladding, InGaIn quantum wells have now been grown under both compressive and tensile strain, as well as no strain at all! This has allowed the experimental investigation of two-dimensional electron gas (2DEG) properties within InGaIn quantum wells that have been subjected to a full range of strain, opening the doors to a new realm of strain engineering. High-optical quality Al_xIn_yGa_{1-x-y}N quaternary films were grown in a vertical MOCVD reactor at atmospheric pressure using nitrogen as the carrier gas. A growth temperature of 875°C was found most suitable for the incorporation of high InN concentrations while still procuring high-quality AlN within the quaternary alloy. The growth of Al_{0.24}In_{0.09}Ga_{0.67}N yielded a quaternary alloy that

was latticed-matched to $\text{In}_{0.8}\text{Ga}_{0.2}\text{N}$ and band-gap-matched to GaN, as determined by X-ray diffraction and room temperature photoluminescence respectively. $\text{Al}_{0.24}\text{In}_{0.09}\text{Ga}_{0.67}\text{N}$ cladding can thus provide the confinement capabilities of GaN cladding without subjecting an $\text{In}_{0.8}\text{Ga}_{0.2}\text{N}$ quantum well to pseudomorphic strain. We present the capacitance-voltage-derived 2DEG properties of several $\text{In}_{0.8}\text{Ga}_{0.2}\text{N}$ quantum wells subjected to tensile strain, compressive strain, and no strain. $\text{In}_{0.8}\text{Ga}_{0.2}\text{N}$ quantum wells clad with GaN exhibit better 2DEG confinement than their $\text{Al}_{0.24}\text{In}_{0.09}\text{Ga}_{0.67}\text{N}$ -clad counterparts. This behavior is attributed to strain-enhanced 2DEG confinement within GaN-clad quantum wells. Additionally, it was found that GaN cladding results in a peak 2DEG concentration that increases fairly linearly with $\text{In}_{0.8}\text{Ga}_{0.2}\text{N}$ quantum well width, suggesting that strain-induced piezoelectric fields are affecting the free electron concentration within GaN-clad wells. In contrast, $\text{Al}_{0.24}\text{In}_{0.09}\text{Ga}_{0.67}\text{N}$ cladding renders a 2DEG concentration that is virtually the same for all $\text{In}_{0.8}\text{Ga}_{0.2}\text{N}$ well widths, suggesting that strain-induced piezoelectric fields are not prominent within $\text{Al}_{0.24}\text{In}_{0.09}\text{Ga}_{0.67}\text{N}$ -clad wells. Of further interest, the 2DEGs for compressive and tensile $\text{In}_{0.8}\text{Ga}_{0.2}\text{N}$ quantum wells are localized at opposite interfaces, which is attributed to strain-induced piezoelectric fields pointing in opposing directions. In light of this finding, the suitability of quaternary cladding for high-performance HEMTs and optoelectronics is explored. We will report on the 2DEG sharpness, peak concentration, and position within compressive, tensile, and unstrained $\text{In}_{0.8}\text{Ga}_{0.2}\text{N}$ quantum wells.

11:00 AM, C4 +

Piezoelectric Effects in AlInGaN/InGaN Quantum Well Structures: *Michael E. Aumer*¹; S. F. LeBoeuf¹; M. Smith²; J. Y. Lin²; H. X. Jiang²; S. M. Bedair¹; ¹North Carolina State University, Dept. of Elect. and Comp. Eng., 232 Daniels Hall, P.O. Box 7911, Raleigh, NC 27695 USA; ²Kansas State University, Dept. of Physics, Manhattan, KS 66506 USA

The vast potential of III-nitrides for optoelectronic, high power, and high frequency devices is well understood. However, our understanding of important device and materials issues involving strain, piezoelectric fields, and recombination mechanisms is less developed. Virtually all studies of InGaN quantum wells have utilized InGaN layers subjected to compressive strain from an underlying layer of GaN or AlGaIn. Therefore, the ability to grow InGaN quantum wells subjected to no strain and even tensile strain is highly desirable. This can be achieved with the use of AlInGaN. The quaternary alloy offers more flexibility for strain engineering of thin films by allowing independent control of the band gap and lattice parameter. The availability of AlInGaN with up to 15% InN and 30% AlN provides sufficient flexibility to investigate the effects of strain on InGaN quantum wells. We report on the effects of strain on the recombination mechanisms in AlInGaN/InGaN quantum well structures. Sample growth was performed in a vertical reactor MOCVD system. An AlN buffer layer was deposited followed by the growth of 2 microns of GaN. AlInGaN and InGaN growth was performed at atmospheric pressure and 875°C with nitrogen as the carrier gas. The AlInGaN/InGaN quantum well structures were grown with different strain configurations, including wells with zero strain and tensile strain. The InN content in the well was 8% for all samples. Analysis was performed using photoluminescence (PL), time-resolved PL, x-ray diffraction, and capacitance-voltage measurements. The peak emission energy varied linearly over the range of strain investigated for all quantum well widths. For 3 nm wells, a change in strain of 0.8% resulted in a peak energy shift of 200 meV. With increased tensile strain, one can conceivably achieve even longer emission wavelengths with only 8% InN in the active layer, thereby facilitating the achievement of a green laser diode. Also, the luminescence intensity of unstrained wells was greater than that for strained wells. Furthermore, the transient luminescence behavior was found to depend strongly on strain. For an unstrained well, the carrier lifetime did not vary significantly with energy near the peak. In contrast, strained wells show an increase of carrier lifetime at energies below the peak energy. We will report on possibilities for strain engineering utilized as a tool for the optimization of device designs.

11:20 AM, C5

Efficient Emission Against the Internal Piezoelectric Field of InGaN/GaN/AlGaIn Single-Quantum-Well Amber Light-Emitting Diodes: *Shigefusa F. Chichibu*¹; Akiko Setoguchi¹; Takashi Azuhata²; Takahiro Deguchi³; Takayuki Sota⁴; Shuji Nakamura⁴; ¹University of Tsukuba, Instit. of Appl. Phys., 1-1-1, Tennodai, Tsukuba, Ibaraki 305-8573 Japan; ²Hirosaki University, Depts. of Matls. Sci. and Tech., 3

Bunkyo-cho, Hirosaki, Aomori 036-8561 Japan; ³Waseda University, Depts. of Elect., Electro. and Comp. Eng., 3-4-1, Ohkubo, Shinjuku, Tokyo 169-8555 Japan; ⁴Nichia Chemical Industries Limited, Dept. of Rsch. and Dev., 491 Oka, Kaminaka, Anan, Tokushima 774-8601 Japan

InGaN alloys are attracting special interest because they serve as active regions of UV and visible SQW LEDs and purplish-blue QW LEDs. Blue, bluish-green, and green InGaN SQW LEDs have already been commercialized and amber and red LEDs were made recently. It is known that output power of AlInGaP amber LEDs decreases approximately one half with the increase of ambient temperature from 0°C to 40°C. However, the output power of InGaN amber LEDs decreases only 20% with increasing temperature from -40°C to 80°C. This improved temperature performance results from the large band discontinuity between the InGaN well and GaN or AlGaIn barriers. Conversely, InGaN visible LEDs in general have two disadvantages. One is the blueshift of the emission peak by the increase of forward current. The other is that external quantum efficiency increases with increasing InN mole fraction from zero (GaN) to 0.1 and levels off at 19% then decreases rapidly with further increase of the emission wavelength longer than 530 nm. These two factors may be due to the presence of internal electric field in the QW due to the piezoelectric polarization; i.e. quantum-confined Stark effects (QCSE). Therefore, it is important to clarify the emission mechanisms in InGaN QW LEDs in order to find the way to obtain improved device performance like higher external quantum efficiency. In this presentation, results of optical spectroscopies on the InGaN amber LEDs will be presented to show the importance of quantum confinement and localized band-tail states where QW excitons recombine radiatively. Important results are as follows: the electroluminescence (EL) peak shows a blueshift by up to 120 meV with increasing forward current, and the EL peak energy does not show remarkable shift with increasing temperature. The device naturally exhibits large Stokes-like shift. When the InGaN well is selectively photo-excited, the PL peak shifts to the higher energy by up to 110 meV by changing the external bias from +2V to -10V. These results suggest the presence of huge internal piezoelectric field, which points from the surface to the substrate. The emission lifetime increases with decreasing the detection photon energy. The EL spectra exhibit exponential tail in the lower energy side, and the higher energy component grows faster than that of the lower energy one with increasing temperature. This may be due to thermal release of the localized QW excitons. Since the well thickness is only 2.5nm, the device exhibits reasonable efficient emission in spite of the presence of the piezoelectric field and large number of threading dislocations.

11:40 AM, C6

Bias Controlled Luminescence Efficiency in Polarized GaInN/GaN Quantum Wells: *Christian Wetzel*¹; Hiroshi Amano²; Isamu Akasaki²; ¹Meijo University, High Tech. Rsch. Ctr., 1-501 Shioyamaguchi, Tempaku-ku, Nagoya 468-8502 Japan; ²Meijo University, Depts. of Elect. and Electro. Eng., 1-501 Shioyamaguchi, Tempaku-ku, Nagoya 468-8502 Japan

The presence of huge polarization charges and associated fields in group-III nitrides exemplifies one of the unusual properties of this successful class of semiconductor. First concluded from the observation of the quantum confined Stark effect in GaInN/GaN, we proposed, demonstrated and quantified the dominant role these charges play in the electronic and optoelectronic properties of the AlGaInN-system. These observations are accompanied by evidence typically associated with structural inhomogeneities, defects, and impurities, and the regimes of respective dominance have yet to be distinguished. Induced by the discontinuities of the polar bond across heterointerfaces polarization charges play a role similar to bandoffsets between components of a heterostructure. The polarization is controlled by alloy composition and biaxial strain and therefore is a major design parameter. This gives both, the opportunity to control the bandstructure at will by polarization design and likely dooms device structures to failure when those effects are neglected. It is therefore a necessity to evaluate the full range of implications. In GaInN/GaN light emitting diodes an unusual saturation of the differential quantum efficiency with bias current has been reported and in GaInN/GaN quantum wells optimized for laser diode structures we observe a possibly related effect. The luminescence efficiency shows a strong dependence on the applied bias voltage. A nature of electroluminescence must be ruled out. In parallel the electric field condition in the layers is monitored by the modulation period of Franz-Keldysh oscillations in reflectivity.

As shown in series of GaInN/GaN and AlGaIn/GaN quantum wells the electric field conditions acting within the layers can accurately be derived from an analysis of photo- or electro-modulated reflection spectra. We find that the large efficiency dynamics supersedes the expected field dependent variation of the dipole matrix element. This suggests that beyond the bandstructure also the carrier dynamics be strongly affected by the electric fields. The most likely mechanism is a drift of photogenerated carriers within the field. The associated threshold energy determined in photoluminescence excitation spectroscopy in turn scales with the quantity of the polarization dipole across the well. We therefore obtain a coherent description of the band structure and recombination channels in such quantum wells. This result should be an important step in the clarification of polarization controlled AlGaInN heterostructures and devices and we conclude that proper device design needs to take full account of polarization properties and associated electric fields. This work was partly supported by the JSPS Research for the Future Program in the Area of Atomic Scale Surface and Interface Dynamics under the project of Dynamic Process and Control of the Buffer Layer at the Interface in a Highly-Mismatched System and the Ministry of Education, Science, Sports and Culture of Japan (contract No. 11480131, and High-Tech Research Center Project).

Session D. Photonic Bandgap Materials

Wednesday AM Room: Centennial Halls
June 21, 2000 Cafeteria

Session Chairs: Laura Mirkarimi, Hewlett Packard, Palo Alto, CA 94304 USA; Theresa Mayer, Penn State University, University Park, PA 16802 USA

10:00 AM, D1 +

Synthesis and Characterization of Inverse FCC Colloidal Photonic Crystals: Ganesh Subramania¹; Kristen Constant²; Rana Biswas¹; Mihail M. Sigalas¹; Kai-Ming Ho¹; ¹Iowa State University, Ames Lab.-USDOE and Dept. of Phys. and Astro., Ames, IA 50011 USA; ²Iowa State University, Ames Lab.-USDOE and Dept. of Matl. Sci. and Eng., Osborne Dr., Ames, IA 50011 USA

Photonic crystals are structures in which the refractive index of the material varies periodically in space. For visible/near-IR photonic crystals the variation in the refractive index of the medium is in the sub-micrometer range. Self-assembly of monodisperse spherical colloidal particles (e.g. polystyrene, silica) into close packed lattice provides an excellent 3-D periodic dielectric structure. We have developed a novel synthesis technique for making photonic crystals using the property of colloidal self-assembly. We start with a binary suspension of monodisperse polystyrene microspheres and aqueous suspension of nanocrystalline titanium dioxide, both of which are commercially available. Few drops of this suspension is spread on a glass substrate and allowed to dry slowly for about 24 hrs. in a high humidity chamber. During the slow drying phase the polystyrene microspheres order into close packed structures simultaneously as the intersphere regions are filled with nanoparticle titania. Drying rate, titania particle size, agglomeration of titania in the suspensions, volume fraction of solids in suspension and sample positioning are factors that determine sample size and quality. Details of how these factors affect sample growth will be discussed in the presentation. The samples obtained are in the form of thin films (10-20 μ) on substrates. The removal of template spheres is accomplished by heat treatment. Visual inspection of the samples made with smaller sized sphere templates reveals uniform bright color characteristic of the sphere diameter. Presence of the photonic gap is demonstrated by measuring the optical reflectivity of the sample using a Perkin Elmer Lambda-9 spectrophotometer. The wavelength of the reflectivity peaks scale very well with the sphere diameter. The specular reflectivity peaks progressively shift towards shorter wavelengths with increasing angle of incidence. There is evidence that thin film sintering effects results in asymmetric shrinkage during densification. Evidence to support this has been observed in the

small angle X-ray scattering (SAXS) data of the photonic crystal sample. SAXS data also indicates that the stacking along the $\langle 111 \rangle$ direction close-packed is FCC rather than HCP or random close-packed. The extent of densification of the background nanocrystalline titania during sintering is obtained by measuring the shift in the reflectivity peak position upon infiltrating the pores with a lower index liquids and comparing it with computer simulation of the structure. Structural characteristics of the sample such as ordering, grain size and grain boundaries were studied by means of scanning electron microscopy. SEM tends to probe smaller areas. The crystal quality over larger area can be studied by observing laser diffraction pattern from the samples. By studying the diffraction spot pattern, shape and intensity distribution we can obtain quantitative information about the individual samples.

10:20 AM, D2 +

Fabrication of GaAs/Al_xO_y Based 3-D Photonic Bandgap Crystal by Single Step Epitaxial growth: Jayshri Sabarinathan¹; Weidong Zhou¹; Boaz Kochman¹; Donghai Zhu¹; Pallab Bhattacharya¹; ¹University of Michigan, Dept. of Elect. Eng. and Comp. Sci., Solid State Electro. Lab., 1301 Beal Ave., Ann Arbor, MI 48109-2122 USA

The development and understanding of photonic bandgap (PBG) crystals offer the possibility of realizing devices such as thresholdless lasers, single mode LED's, filters and other novel structures. One of the challenges is realizing 3-D PBG crystals in III-V direct electronic bandgap material systems such as GaAs in which the radiative efficiency is high and with features sizes in the sub-micron range for near-infrared optoelectronic applications. A relatively simple and robust processing technique for compatibility and integration with standard fabrication processes is also needed. Recently, many schemes have emerged to fabricate semiconductor based 3D PBG crystals[1,3]. However the techniques reported so far have been either Si-based which limits its applications to active optoelectronic devices, involving arduous multiple growth steps, or not scalable to sub-micron feature sizes. We describe here a simple fabrication scheme to produce a GaAs-based face-centered-cubic photonic crystal using single step epitaxial growth. The PBG crystal is fabricated by first etching a (001) GaAs substrate in a checkerboard pattern. Patterns with feature sizes of 3 μ m, 1.5 μ m and 0.5 μ m feature sizes were made using optical and electron-beam lithography and etched to a depth of 0.55 μ m using reactive ion etching (RIE). 4-5 periods of alternating 0.5 μ m Al_{0.98}Ga_{0.02}As/0.5 μ m Al_{0.18}Ga_{0.82}As are deposited using molecular beam epitaxy (MBE). The Al_{0.98}Ga_{0.02}As layers are then preferentially oxidized to form stable Al_xO_y with a refractive index of ~1.5 using ridge formation and wet oxidation. We have created a 3-D face-centered-cubic photonic crystal in which lattice site regions of refractive index ~3.55 are embedded in an Al_xO_y matrix of refractive index 1.5. The index contrast is therefore ~2. The success of this technique crucially depends on the growth kinetics of the adatoms on the patterned substrate. We have found that the ideal situation is the case where at least the Al_{0.98}Ga_{0.02}As layer maintains continuity over the whole pattern to allow it to be oxidized. We chose Al_{0.18}Ga_{0.82}As instead of GaAs as the high index material since the former provides the right growth kinetics. Fourier Transform Infrared (FTIR) spectroscopy was performed at room temperature on the PBG samples. A transmission dip between 2.5-3 μ m is observed for the samples with the larger periodicity (3 μ m). The transmission characteristics have features of a pseudogap and this probably results from the process-induced disorder. The measured attenuation is 2dB. The angular dependence of the transmission spectrum of the photonic crystal was also investigated. Measurements were made at angles θ ($0 \leq \theta \leq 25^\circ$) to the surface normal. We observe that the transmission dip occurs at the same wavelength but that the depth of the gap is reduced as the sample is rotated. The change in attenuation with rotation shows that it is probably a pseudogap. Measurements of the 1.5 μ m and 0.5 μ m PBG crystals are in progress and will also be presented. [1] E. Yablonovitch, J. Opt. Soc. Am. B 10,283 (1993) [2] S.Y. Lin et al., Nature 394,251(1998). S. Noda et al., Jpn J. Appl Phys. 36, L909 (1996) [3] S.Kawakami, Electronics Letters 33,1260 (1997). Work supported by the Office of Naval Research.

10:40 AM, D3 +

Fabrication and Characterization of ZnSe-Based Whispering Gallery Mode: Oindrila Ray¹; Andrei A. Sirenko¹; Joseph J. Berry¹; Nitin Samarth¹; Kevin D. Maranowski²; Eric Dennis²; A. C. Gossard²; David D. Awschalom²; ¹Pennsylvania State University, Phys. Dept., 104 Davey

Lab., State College, PA 16802 USA; ²University of California, Santa Barbara, CA 93106 USA

Semiconductor microdisks that support whispering gallery modes (WGMs) have traditionally been of interest for potential opto-electronic applications such as lasers. More recently, such patterned structures have elicited renewed interest within a quantum computation scheme that relies on exploiting the coupling between quantum dot states and WGMs [PRL 83,4204(1999)]. ZnSe-based microdisks provide an attractive medium for such studies due to their characteristically large oscillator strengths and optical non-linearities. Here, we describe the fabrication and characterization of ZnSe microdisks (diameters in the range 4-8 microns) that incorporate CdSe quantum wells (QWs) and quantum dots (QDs) as the intracavity active medium. The heteroepitaxy of ZnSe/CdSe quantum structures on a GaAs/AlGaAs epi-substrate provides the foundation from which microdisks are patterned using a combination of optical lithography and both dry and wet etching schemes. Surface characterization of the microdisks is performed by SEM, while steady-state photoluminescence (PL) at low temperatures probes the confined optical modes. In microdisks with CdSe QWs, PL spectra predominantly consist of WGMs (both TE and TM modes), indicating a high degree of light confinement, with Q factors estimated at about 3500 for RIE etched cavities. In addition, lossy TE and TM radial modes due to cavity coupling with the (Ga,Al)As pedestal are also seen. We discuss the challenges of incorporating Stranski-Krastonow QDs in II-VI microdisks, wherein subtle changes in the strain configuration appear to dramatically affect QD formation. Finally, we compare the effects of wet- and dry-etching schemes on the Q factors of these microdisks. Supported by grant ARO-DAAG55-98-1-0366.

11:00 AM, D4

Si/SiO₂ Microcavity for Luminescence Enhancement of Er-Doped Materials: Michal Lipson¹; Kevin M. Chen¹; Lionel C. Kimerling¹; ¹MIT, DMSE, 77 Massachusetts Ave., Cambridge, MA 02139 USA

Er³⁺ produces a temperature independent, sharp line emission that has been demonstrated as an ideal Si and glass-like optical dopant materials. One of the strong limitations of the use of Er in microphotonic devices is the concentration quenching of the luminescence in highly Er-doped structures. In this work the luminescence of Si:Er and Er₂O₃ was studied. When pumped with a 488nm pump source, the materials present a strong sharp luminescence at 4K around 1.54 microns. When the temperature is increased the luminescence quenches heavily. We find this luminescence quenching to be due to up-conversion mechanism involving multi-phonon emission. In order to suppress the luminescence quenching we used Si/SiO₂ microcavity in resonant with the 1.54 microns Er³⁺ transition. The light confinement induces a decrease in the Er³⁺ radiative lifetime favoring the radiative processes over the non-radiative ones. The structure consists of a thin Er₂O₃ embedded between two 3-period of Si/SiO₂ quarter wavelength stack. The Q of the cavity is measured to be 200. We find a decrease in the Er³⁺ radiative lifetime by an order of three due to the presence of the cavity. A luminescence intensity enhancement of about a factor of 10 is observed at 4K. This enhancement is increased with temperature. At 300K the enhancement is more than two orders of magnitude. A model describing the competition between the radiative process and the up-conversion mechanism explains the suppression of the cavity's luminescence quenching. The cavity's weak temperature dependence, combined with the amplification of the light due to the cavity effect on the radiative modes explains the strong photoluminescence observed at room temperature. The results show that under specific light confinement conditions, the concentration quenching of the luminescence of highly Er-doped structures can be suppressed. This opens the door to the use of highly Er-doped structures in microphotonic applications.

11:20 AM, D5

Fabrication of a One-Dimensional Photonic Bandgap Material by Pulsed Laser Deposition: René Lopez¹; Ricardo Ruiz¹; Leonard C. Feldman¹; Richard F. Haglund¹; ¹Vanderbilt University, Dept. of Phys. and Astro., 6301 Stevenson, Nashville, TN 37235 USA

Photonic bandgap structures are promising materials for a wide variety of optical and electro-optic applications, including optical switches, optical filters and transparent conductors. We have fabricated a one-dimensional metallo-dielectric photonic bandgap structure often called a Bragg mirror for the first time by means of pulsed laser deposition (PLD).

is well suited to growing multicomponent films and particularly useful for fabricating layered structures of disparate materials. Our multilayer stacks consisted of as many as five periods of Ag/Al₂O₃, with thicknesses ranging from 25-40 nm per layer. Thickness and composition were specified by computer control of the PLD system, and verified using Rutherford backscattering spectroscopy (RBS) profiling. In benchmarking the growth process, we have compared RBS, ellipsometry and spectrophotometry measurements for single layers, finding agreement within $\pm 10-15\%$ for both metallic and insulating films. We have also used scanning electron and atomic-force microscopies to study the mechanism of film growth and to correlate composition and morphology with electrical and optical properties. We were able to tune the pass bands and the bandgap over a broad range of optical wavelengths depending on layer thickness and stack configuration, as reported elsewhere. Transmittance spectra for the photonic bandgaps are in good agreement with standard matrix-transfer calculations, provided that the metal layers are not too thin (≥ 15 nm). A particularly promising property of these photonic bandgap materials is that they can not only be tuned to a desired range of wavelengths, but might also be useful as transparent conductors. We find excellent values of the conductivity when the Ag layers have thicknesses of order 15 nm. For a single-cavity etalon structure, the conductivity is similar to that of common metals, of order 10^6 (W \cdot cm)⁻¹. A particularly intriguing possibility for materials made in these one-dimensional configurations is the possibility of making nonlinear photonic bandgap materials by incorporating a nonlinear element into the insulating layers. We plan to attempt this by embedding metallic nanocrystals, configured in regularly spaced arrays, into the alumina layers. Computational studies of the growth processes involved in nucleating and growing uniformly sized and spaced dots show that substrate temperature, surface overpressure and ablation conditions can all be expected to have an influence on the experimental results. Research supported by the National Science Foundation (DMR-9871234) and the College of Arts and Science at Vanderbilt University.

11:40 AM, D6

A Model of a Two Dimensional Photonic Bi-Oriented Crystal: P. Kopperschmid¹; L. C. Kimerling¹; ¹Massachusetts Institute of Technology, 77 Mass. Ave., Cambridge, MA 02139 USA

A photonic crystal concept is supposed, assuming a stack of two rotated dielectric layers of one single highly anisotropic material. Here, the crystallographic twist between the layers result in a contrast of the optical constants. Extending the concept of dielectric contrast by crystallographic contrast in two directions, a new two-dimensional photonic crystal is developed. The dielectric constant between the rotated and unrotated layers varies with the rotation angles and with the direction of the light propagation. Therefore, in certain directions a electromagnetic wave propagates through a bi-crystalline structure without dielectric contrast and the optical bands are closed. The photonic bi-crystal integrates the optical properties of a homogenous transparent dielectric and the properties of a photonic crystal. In the photonic bi-crystal integrates the optical properties of a homogenous transparent dielectric and the properties of a photonic crystal. In the photonic bi-crystal, light confinement and coupling of electromagnetic modes are related to the crystallographic symmetry and light propagation. Two calculated photonic band structures of a two-dimensional checkerboard-structured photonic bi-crystals are presented based on the data of hexagonal calcite. First, the rotated grains of the photonic bi-crystal are twisted 90° around the surface normal of the two-dimensional photonic crystal with respect to the unrotated grains. According to the point-symmetry of the photonic structure, the propagating TE and TM modes are coupled along all four directions Γ -M (The diagonals of the reduced Brillouin zone). Light confinement is achieved along directions between the diagonals. Second, the rotated grains are twisted by 90° perpendicular to the surface normal. The corresponding two-dimensional reduced Brillouin zone is symmetric to Γ -X and Γ -X' (The main axis of the reduced Brillouin zone). Here, maximal dielectric contrast for light propagation is observed along Γ -X. No dielectric contrast, however, is observed perpendicular to Γ -X. In principle, spontaneous emission or light emission can be suppressed or amplified for selected directions of light propagation.

Session E. Organic Materials and Devices - I

Wednesday AM Room: Driscoll Center
June 21, 2000 North - Pub

Session Chairs: George Malliaras, Cornell University, Depts. of Matls. Sci. and Eng., Ithaca, NY 14853-1501 USA; Shelby Nelson, Xerox Corporation, Webster, NY 14580-9720 USA

10:00 AM, E1 *Invited

Mechanism of Long-Term Degradation in Small Molecule Based OLEDs Studied by Time Resolved Fluorescence: *Zoran D. Popovic*¹; Hany Aziz¹; Nan-Xing Hu¹; Paulo DosAnjos¹; Andronique Ioannidis²; ¹Xerox Research Centre of Canada, 2600 Speakman Dr., Mississauga, Ontario 00229 Canada; ²Xerox Corporation, Webster, NY USA

Intrinsic degradation, which leads to the long-term decrease in the electroluminescence (EL) efficiency of the devices, has been a major limitation facing the new technology of organic light emitting devices (OLED). Traditionally, degradation has been speculated to be caused by morphological instability of the organic layers, especially the less stable hole transport layer (HTL), or by the formation of deep traps at the hole-injecting contact. These speculations were based on experimental observations showing that doping of the organic layers or introducing a buffer layer at the hole injection contact can dramatically improve the device stability. However, the true causes of OLED degradation remained uncertain. Recently we studied long-term degradation mechanism of organic light emitting devices based on tris(8-hydroxyquinoline) aluminum (AlQ₃), a widely used electroluminescent small molecule. These studies show that injection of holes in AlQ₃ is the main factor responsible for device degradation, which was verified by constructing devices where predominantly holes were transported through a 5 nm thick AlQ₃ layer. These devices showed a significant decrease in the photoluminescence (PL) efficiency of the AlQ₃ layer upon prolonged current flow. In contrast, similar devices constructed in such a way to allow only electron flow through AlQ₃ did not show any decrease in photoluminescence efficiency under similar current driving conditions. Consequently, this proves that AlQ₃ cations are unstable and their degradation products lead to device degradation. In the present work we will report recent results on time resolved fluorescence and comparison between fluorescence and electroluminescence decay of AlQ₃ based devices. These results show that the AlQ₃ degradation products are fluorescence quenchers, which causes decrease in device efficiency during prolonged operation. We also observed the PL decay is consistently smaller than EL decay indicating that degradation of AlQ₃ also leads to formation of charge recombination centers.

10:40 AM, E2

Device Performance and Polymer Morphology in Polymer Light Emitting Diodes: The Control of Thin Film Morphology and Device Quantum Efficiency: *Y. Shi*¹; *J. Liu*¹; *Y. Yang*¹; ¹University of California-Los Angeles, Depts. of Matls. Sci. and Eng., Los Angeles, CA 90095 USA

We present the results of a systematic study on how the processing conditions of spin-casting affect the morphology of the polymer thin films, and how the morphology affects the polymer light-emitting diode (LED) performance. The absorption peaks of MEH-PPV (poly(2-methoxy-5-(2'-ethyl-hexyloxy)-1,4-phenylene vinylene) thin films, which reflects the conjugation of π -electrons, are strongly correlated to the spin-casting conditions. At high spin speed, better conjugation is observed. In addition, the photoluminescence emission peak of MEH-PPV films at ~630 nm has a strong correlation to polymer aggregation. By proper selection of organic solvents, polymer solution concentrations, and spin speeds, we are able to control the aggregation of the polymer chains. Subsequently, we are able to control the emission color and the quantum efficiency of the MEH-PPV LEDs, by simply adjusting

the spin-casting conditions. Although spin-casting is the most commonly used technique for the preparation of polymer thin films, our finding suggests that the thin-film preparation, and thus the formation of polymer morphology, is a much more complicated process than previously assumed.

11:00 AM, E3

High Performance Polymer Photovoltaic Cells Photodetectors and Image Sensors: *G. Yu*¹; *G. Srdanov*¹; *H. Wang*¹; *Y. Cao*¹; *A. J. Heeger*¹; ¹Uniax Corporation, 6780 Cortona Dr., Santa Barbara, CA 93117-3022 USA

We report recent progress on polymer photovoltaic cells, photodetectors and image sensors. By improving the photoactive material and the device structure, the energy conversion efficiency of polymer photovoltaic cells was improved significantly to over 4% (500 nm, 10 mW/cm²). Polymer photodetectors with sandwich configuration show high photosensitivity (0.2-0.4 A/Watt in visible and UV), low dark current (0.1-1 nA/cm² at low bias), large dynamic range (>8 orders of magnitude), linear intensity dependence, low noise level and fast response time (to nanosecond time domain). These numbers are comparable to or even better than their inorganic counterparts. Encapsulated devices show lifetime of more than 1.5 years. The advantages of low manufacturing cost, large detection area, easy hybridization and integration with electronic or optical components make them promising for numerous applications including biosensors, full-color digital image sensors, industrial scanners and high energy radiation detectors. Engineering prototypes have been developed. Their performance parameters will be discussed.

11:20 AM, E4

Nanoscale Photocurrent Spectroscopy and Mapping of Organic Semiconductors: *Denis Fichou*¹; *Fabrice Charra*²; ¹CNRS, Lab. des Matériaux Moléculaires, Thiais, France; ²DRECAM, CEA Saclay, Gif sur Yvette, France

Conjugated oligomers and polymers are potentially useful for device applications such as light emitting diodes, field-effect transistors or solar cells. Since microscopic order plays a central role in carrier dynamics, exploring electronic phenomena at a local scale is essential. We report here on the use of scanning tunneling microscopy (STM) in combination with laser excitation to image simultaneously local photocurrents and surface morphology in molecular semiconductors at the nanometer scale. Our home-built light-assisted STM setup operates on a fast two-step data acquisition mode and its high sensitivity allows to visualize the extremely weak tunneling currents (a few pA) typical of low mobility materials such as organic semiconductors. It also provides a direct through space access to the I/V and I/Z characteristics (Z =tip-sample distance) at each point of the scanned area. The {STM tip/air gap/sample} constitutes a MIS junction whose geometry can be modulated by varying the tip-sample distance Z . We reveal in particular the strong photocurrent reduction along the step edges of sexithiophene and pentacene thin films UHV-deposited on Au(111) due to localized surface recombination centers while photocurrent is maximum on top of the defect-free terraces.

11:40 AM, E5

Electroluminescence of Derivatives of 8-Hydroxyquinoline Aluminum: *Guangming Wang*¹; *Junzhe Hu*²; *Yuanzhen Xiang*²; *Xhunwei Yuan*²; *Zuhong Lu*²; *Xiangzhen Sun*³; ¹Nanyang Technological University, Adv. Matls. Rsch. Ctr., Sch. of Appl. Sci., Nanyang Ave. 639798 Singapore; ²Southeast University, Lab. of Molecular and Biomolecular Elect., Nanjing 210096 PRC; ³Nanjing University, Org. Chem. of High-Purity Met. Lab., Nanjing 210008 PRC

Since the first reported two-layer organic electroluminescent (EL) device was developed by using low-weight molecular EL organic material, i.e., 8-hydroxyquinoline aluminum (Alq₃) in the mid-1980's, it has been recognized as one of the most promising next-generation flat panel display systems. After that, a lot of EL devices relative to the Alq₃ were researched widely by using the vacuum evaporation method. In addition, it was also known as n-type material and was extensively used in the multilayer EL devices as an electron-transport layer. However, relating to this high symmetric structure molecule (Alq₃), in this work, we study EL properties of the no-symmetric derivatives of 8-hydroxyquinoline aluminum (Alq₂CH₃ and Alq(CH₃)₂), i.e., one- or two-8-hydroxyquinoline is replaced by methyl group in the Alq₃, and compared their EL properties. Based on these results, it can be also considered that for the multilayer EL devices, the suitable derivative of 8-hydroxyquinoline alumi-

num used as electron hole-transport layer could be selected according to the requirement of energy for getting a high EL efficiency device.

Session F. Oxides of Compound Semiconductors

Wednesday AM Room: Centennial Halls Main
June 21, 2000 Lounge

Session Chairs: Evelyn Hu, University of California-Santa Barbara, Dept. of Elect. Eng., Santa Barbara, CA 93106 USA; Carol Ashby, Sandia National Laboratories, Albuquerque, NM 87185-0603 USA

10:00 AM, F1

Atomic Scale Self-Propagated Oxidation on Silicon Carbide and Abrupt SiO₂ Interface Formation: *P. Soukiassian*¹; F. Amy¹; H. Enriquez¹; Yeu-kuang Hwu²; F. Semond³; C. Brylinski⁴; ¹Universite de Paris-Sud, Commissariat a l'Energie Atomique, Orsay, France; ²Academia Sinica, Taipei and Synchrotron Radiation Rsch. Ctr., Hsinchu, Taiwan; ³Universite de Paris-Sud, CNRS-LPPM, Orsay, France; ⁴Thomson-CSF, Orsay, France

Surface passivation is a central issue in successful SiC device applications. Thanks to the exceptional properties of silicon dioxide, the most promising passivation is expected to be achieved by surface oxidation. However, the latter might result in mixed Si and C oxides products for SiC due to the presence of a binary compound. We investigate the oxidation of the Si terminated 6H-SiC(1000)3x3 surface by core level and valence band photoemission spectroscopies using synchrotron radiation and by room temperature atom-resolved scanning tunneling microscopy (STM). At the atomic scale, the STM study of oxygen interaction with the cubic 3C-SiC(100)3x2 surface is found to be significantly anisotropic with a propagation 40% faster along dimer rows. Initial oxygen atoms interact with surface defects leading to the formation of other defects having the same nature. The latter defects turn to become reactive sites upon further oxygen deposition leading to a self-propagating oxidation process [1]. For the hexagonal 6H-SiC(1000)3x3 surface reconstruction, the STM study indicates that the oxidation process with increasing oxygen exposures is propagating in an isotropic manner which, interestingly, significantly differs from that of cubic 3C-SiC(1000)3x2 surface [1]. The oxide growth is performed by oxygen exposures at room and elevated surface temperatures (from 25°C to 600°C). Unlike silicon surfaces, 6H-SiC(1000)3x3 is taking place already at very low oxygen exposures. As for the 3C-SiC(100)3x2 surface [2], the oxidation rate is significantly enhanced at increasing surface temperatures. The results also indicate that the direct oxidation of the 6H-SiC(0001)3x3 surface leads to SiO₂ formation at low temperatures (500°C) with a non abrupt interface having significant amounts of mixed (Si-O-C) and intermediate (Si 3+, Si 2+, Si+) oxidation products. In contrast, C-free and a much more abrupt SiO₂/6H-SiC(0001) interface formation is achieved when pre-deposited Si overlayer is thermally oxidized at low oxygen exposures and low temperatures (500°C) [3]. Finally, the oxynitridation of silicon carbide surfaces is investigated by XPS. The results indicate that the oxynitridation depends very much of surface composition and structure. Thermal annealing results Si-oxynitride/SiC interface with a nitridation layer located at the interface.

10:20 AM, F2 +

Effects of Mixed Carrier Gas in Wet Thermal Oxidation of AlGaAs: *Yong Luo*¹; Douglas C. Hall¹; Olga Blum²; Hong Hou²; ¹University of Notre Dame, Dept. of Elect. Eng., 275 Fitzpatrick Hall, Notre Dame, IN 46556-5637 USA; ²Sandia National Laboratory, P.O. Box 0603, Albuquerque, NM 87185-0603 USA

In the wet-thermal oxidation of AlGaAs for optoelectronic and electronic devices, ultra high purity N₂ is typically used as the H₂O carrier gas. It is well known that O₂ carrier gas fully suppresses lateral oxidation, and

that air (80:20 N₂:O₂) as a carrier will result in rough surface oxides. We have investigated wet oxidation with controlled addition of trace amounts of O₂ using two 1 μm thick Al_xGa_{1-x}As samples (x=0.3 and 0.8) grown via MOCVD. Surface oxidation of the AlGaAs layers is performed at 450°C after chemically removing a 50 nm GaAs cap layer. The resulting oxides are characterized with a Metricon prism coupler (index and thickness), a scanning electron microscope (thickness), and an atomic force microscope (surface roughness). High and low index x=0.3 oxide films are also characterized by hydrogen forward scattering (HFS). Our results show strong, favorable dependencies of oxidation rate, oxide surface roughness, and film index on the O₂ concentration in the mixed carrier gas for Al_{0.3}Ga_{0.7}As. As the O₂ level increases to about 8000 parts per million (ppm), the oxidation rate increases linearly over one order of magnitude (from 1.77 to 17.9 nm/min) while the oxide surface mean roughness decreases from 0.43 to 0.12 nm. Above 8000 ppm O₂, the oxidation rate decreases and surface roughness increases. The refractive index increases rapidly from 1.49 to 1.67 with just 500 ppm O₂ and remains near this value with up to 1% O₂ added. For Al_{0.8}Ga_{0.2}As, the dependencies of oxidation rate and oxide surface roughness on O₂ content follow similar but less pronounced trends, with very little refractive index change. Between 0 and 6000 ppm O₂ concentration, the oxidation rate increases (from 30.2 to 43.5 nm/min) with nearly identical slope [0.0022 nm/(min-ppm O₂)] as that of Al_{0.3}Ga_{0.7}As. Given the dissimilar oxidation potentials of Al and Ga, this suggests that the role of added O₂ may be to enhance the formation of volatile arsenic oxide necessary for As removal. The oxide growth rate with more than 1% O₂ decreases, and may be sublinear due to the formation of denser oxide films. At 2% O₂, the oxide thickness appears to saturate or terminate at a depth of about 350 nm, consistent with a diffusion-limited oxide growth. As HFS studies show little change in the H content (about 10-12%) of high and low index x=0.3 films, an hydroxide to oxide phase transition appears unlikely. As an observed modification during HFS with higher beam intensities of only the low index oxides is consistent with a more porous dielectric, we believe the effects observed are related to a variation in the porosity of the oxidized films. Finally, O₂ addition is demonstrated for the fabrication of reduced-loss fully-oxidized AlGaAs heterostructure planar waveguides.

10:40 AM, F3

Residual As and the Electrical Characteristics of AlGaAs Native Oxides for MOS Applications: *Pedro J. Barrios*¹; Seong-Kyun Cheong²; Douglas C. Hall¹; Nathaniel C. Crain¹; Gregory L. Snider¹; Christine B. DeMelo¹; Tomohiro Shibata²; Bruce A. Bunker²; Uttiya Chowdhury³; Russell D. Dupuis³; Gary Kramer⁴; Nada El-Zein⁴; ¹University of Notre Dame, Dept. of Elect. Eng., Notre Dame, IN 46556 USA; ²University of Notre Dame, Dept. of Phys., Notre Dame, IN 46556 USA; ³The University of Texas at Austin, Microelect. Rsch. Lab., Austin, TX 78712 USA; ⁴Motorola, Inc., Phys. Sci. Rsch. Lab., Tempe, AZ 85284 USA

Development of GaAs-based metal-oxide-semiconductor (MOS) devices requires a good understanding of the function of their conforming materials, as well as the behavior and properties of their interfaces. We present our study of the quality of field oxides formed by lateral oxidation of Al_{0.98}Ga_{0.02}As and the nature of residual As as analyzed by x-ray absorption fine-structure spectroscopy (XAFS) and x-ray absorption near-edge structure (XANES) measurements. It has been shown by Ashby et al. that the amount of As within 2 μm thick surface oxidized films is higher for partially-oxidized films, with levels dropping after oxidation is complete. Thus, some additional time beyond the required oxidation time may also be beneficial to allow As reaction products to diffuse out of the oxide for our laterally oxidized films (with lateral oxidation lengths of 25-50 μm). Comparative current-voltage (I-V) and capacitance-voltage (C-V) measurements performed on MOS capacitors fabricated with laterally oxidized 50 nm Al_{0.98}Ga_{0.02}As films show that the oxide resistivity and the density of interfacial As_{Ga} antisite defects is indeed strongly sensitive to processing conditions. A 5 order of magnitude reduction of the leakage current density to 1.5 x 10⁻³ A/cm² (37 nA at +3V, A=2400 μm²) is observed for a 10 min anneal in dry N₂ immediately following wet oxidation. C-V data also suggests that the interfacial As_{Ga} antisite is present in untreated oxides but not detectable in annealed oxides. The leakage for annealed films is several orders of magnitude smaller than for unannealed films at both DC and 1 MHz. Although leakage current densities are 3-5 decades lower than reported to date in native-oxide based MOSFETs, the insulating properties of thicker (250 nm) native oxide films as reported by Ashby et al. are significantly and disproportionately better (as low as

3×10^{-9} A/cm²). This apparently strong nonlinear thickness dependence may provide clues to understanding the bulk oxide leakage mechanism in these films. Using XAFS and XANES measurements we have identified the As site within a surface oxidized 0.5 μm $\text{Al}_{0.96}\text{Ga}_{0.04}\text{As}$ film. We observe close to a 50-50 mix of amorphous As_2O_3 and As_2O_5 , and no detectable elemental As precipitates. As_2O_3 decomposes to As_2O_5 at 315°C, and has not previously been identified in the literature as a possible intermediate volatile reaction product involved in As removal during the wet thermal oxidation of AlGaAs. We have observed in other work that the addition of small amounts of O_2 during oxidation enhances oxidation rates and oxide quality (greater density and reduced surface roughness). The explanation of this effect may be tied to the role of As_2O_3 vs. As_2O_5 in As removal from the oxidizing films. Further work is needed to fully understand the role of and limitations posed by residual As in the conductivity and interface quality of these oxides.

11:00 AM, F4 +

Oxidation of Antimonide-Based Semiconductors on InP Substrates: Sheila K. Mathis-Yu¹; Aaron Lau¹; Eric Hall¹; Guilhem Almuneau¹; Evelyn L. Hu²; James S. Speck¹; ¹University of California, Mats. Dept., Santa Barbara, CA 93106 USA; ²University of California, ECE Dept., Santa Barbara, CA 93106 USA

This study focuses on the wet lateral oxidation kinetics of AlAsSb lattice-matched to InP, with the goal of creating a planar, stable oxide suitable for allowing relaxation of strained capping layers. AlAsSb oxidation was carried out for temperatures from 350-500°C, times from 10 to 300 minutes, layer thicknesses of 200 to 2000Å, and varying Ga content. Prior studies of wet oxidation of AlAsSb show nonuniform segregation of Sb at the oxide-semiconductor cap interface. The Sb layer disrupts the planarity of the capping layers after oxidation. Oxidation structures consisted of a 2000Å GaAsSb buffer, an oxidation layer, and a 2000Å GaAsSb cap, all lattice-matched to the InP substrate, as confirmed by X-ray diffraction. Oxidation layer thicknesses of 100Å to 2000Å were used, but oxidation of layers less than 200Å thick was not observed. This is consistent with prior studies that found a similar minimum thickness for AlGaAs oxidation. Thinner layers (i.e., 200Å and 300Å) had nonplanar oxidation fronts and Sb segregation. In addition the oxidation of $\text{Al}_{1-x}\text{Ga}_x\text{AsSb}$ was also studied with $x = 2, 5, \text{ and } 10\%$. For AlAsSb, the oxidation is reaction-limited with a measured activation energy of 1.46 eV in the range 325-400°C, compared with AlGaAs, for which an activation energy of 1.6 eV has been found in other studies. We report for the first time that at high temperatures ($T_{\text{ox}} > 450^\circ$), AlAsSb oxidation is self-limiting, meaning that oxidation proceeds for a distance on the order of 50 μm and then stops. The Sb layer is 25±5% of the thickness of the original AlAsSb layer independent of oxidation temperature, time, layer thickness or composition. Alternative structures, including superlattices of AlAs/AlSb and of AlAsSb/GaAsSb, and quaternary AlInAsSb alloys were investigated to reduce antimony segregation and planarize the structure. This study shows that antimony segregation is not affected by easily alterable processing parameters such as oxidation temperature, time, or layer thickness.

11:20 AM, F5 +

Thermal Wet Oxidation of Al_{0.4}Ga_{0.6}P: John Henry Apple¹; Kuo-Lih Chang¹; Greg W. Pickrell¹; K. Y. Cheng¹; K. C. Hsieh¹; ¹University of Illinois, Elect. and Comp. Eng., 208 N. Wright St., Rm. 319B, Urbana, IL 61801 USA

For decades the oxidation of many compound semiconductors has been investigated to yield native oxides for different applications. Most beneficial has been the study of laterally oxidizing $\text{Al}_x\text{Ga}_{1-x}\text{As}$ which has led to many breakthroughs in applications such as distributed Bragg reflectors (DBRs) for vertical cavity surface emitting lasers (VCSELs), current confinement, buried insulators, and strain relaxation. Less extensive work has been done to study the materials grown on GaP. Rubenstein and Kato et al. have experimented with thermally oxidizing GaP. However the oxide, consisting mostly of GaPO_4 , was cracked and did not adhere well. It was reported the damage was caused by the loss of gaseous P_2O_5 . In this work thermal wet oxidation of GaP and $\text{Al}_{0.4}\text{Ga}_{0.6}\text{P}$ has been studied and compared. Oxidations done at 650°C for both materials indicate an oxidation rate of about 55 nm/hr for GaP and 80 nm/hr for $\text{Al}_{0.4}\text{Ga}_{0.6}\text{P}$. It should be noted that these rates represent the growth of the oxide layers and not the consumption of the material oxidized. In contrast to the oxidation of GaP, morphology of oxidized $\text{Al}_{0.4}\text{Ga}_{0.6}\text{P}$ is con-

siderably improved. This is plainly seen by an optical microscope and transmission electron microscopy (TEM). When comparing this material to $\text{Al}_x\text{Ga}_{1-x}\text{As}$ great differences are found in the diffusion of materials during oxidation. When $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is oxidized As_2O_3 is formed and diffuses out of the material leaving Al_2O_3 and Ga_2O_3 . This results in volume shrinkage to about 90% its original volume. When GaP is oxidized the product is found to be $\text{GaPO}_4 \cdot 2\text{H}_2\text{O}$ identified by TEM diffraction. The oxide thickness swells to 2.5-3 times its original volume. When $\text{Al}_{0.4}\text{Ga}_{0.6}\text{P}$ is oxidized, the Ga most likely forms $\text{GaPO}_4 \cdot 2\text{H}_2\text{O}$. The left over Al and P are believed to be in the form of Al_2O_3 and P_2O_5 as well as some elemental phosphorous. The P_2O_5 is volatile at the oxidation temperature and some will diffuse out of the sample. The elemental phosphorous diffuses into the substrate. This material expands to roughly twice its original volume. The difference in surface roughness of the two oxides may be a result of the different expansion ratios. In a separate experiment pure AlP was laterally oxidized and it was found that the residual product of this oxidation was Al_2O_3 with little phosphorous in the sample causing volume shrinkage. Thus there is less expansion in the $\text{Al}_{0.4}\text{Ga}_{0.6}\text{P}$ than in the GaP leading to an improved morphology.

11:40 AM, F6

Characterization of Native-Oxide/GaN and CVD-SiN_x/GaN Interfaces: Tamotsu Hashizume¹; Ryuusuke Nakasaki¹; Susumu Oyama¹; Hideki Hasegawa¹; ¹Hokkaido University, Rsch. Ctr. for Interface Quan. Elect. (RCIQE) and Grad. Sch. of Elect. and Info. Eng., Kita-ku North 13 West 8, Sapporo, Hokkaido 060-8628 Japan

GaN-based electronic devices such as FETs and HEMTs have attracted much attention recently due to many important applications in high-power/high-frequency field. However, there still remain underlying issues on device processing technologies such as formation process of stable metal contacts, etching processes, surface passivation process, etc. Although understanding of oxidation and passivation processes are indispensable for development of these processing technologies, surface and/or interface properties of GaN-related materials has not been explored in detail. In this paper, native-oxide/GaN and CVD-SiN_x/GaN interfaces were systematically characterized by x-ray photoelectron spectroscopy (XPS), Raman spectroscopy and capacitance voltage (C-V) methods. Si-doped GaN layers ($n = 1 - 3 \times 10^{17} \text{ cm}^{-3}$) grown on sapphire substrates by metal organic chemical vapor deposition (MOCVD) were used. Native-oxide/n-GaN structures were formed in the dry O_2 flow in a quartz tube furnace. Temperatures of 600°C and 900°C were chosen for study for 30 min exposure. SiN_x/n-GaN structures were prepared by electron cyclotron resonance (ECR) plasma CVD using N_2 and SiH_4 . Just prior to the deposition of insulating films, some GaN surfaces were treated in NH_4OH -based solution at 50°C for 5-15 min, in ECR N_2 plasma for 1-15 min and in ECR H_2 plasma for 1-15 min. After the oxidation at 600°C, the XPS Ga3d peak was found to slightly shift toward the higher binding energies, while no significant change in the N1s spectra was observed. The samples oxidized at 900°C exhibited a large peak shift (0.7eV) in the Ga3d level and the increase of the O1s intensity. In addition, the N1s peak was almost hidden by the Ga AES peak with the oxidized phase. These results indicated that the growth of the native oxide (Ga oxide) progressed at temperatures higher than 900°C. The intensity of the E_2 Raman peak from the GaN lattice was found to decrease after the oxidation at both 600°C and 900°C. The XPS study exhibited that the NH_4OH -based surface treatment is very effective in removing natural oxides from the GaN surface. Surface treatments in the ECR N_2 plasma and H_2 plasma could also decrease natural oxide components. The ECR-CVD SiN_x/n-GaN structures prepared after these surface treatments showed good C-V characteristics. Clear deep depletion behavior was observed at room temperature, similar to that of the SiO_2/SiC interfaces. A minimum Dit value of $1 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$ or less was realized around the energy position of $\text{E}_c - 0.8 \text{ eV}$ in the SiN_x/n-GaN structures. The detailed XPS core-level measurement revealed that the valence band offset was estimated to be 1.0-1.2eV at the SiN_x/n-GaN interface, indicating the type-I band lineup suitable for the surface passivation structure for GaN.

Session G. MID-IR Devices - II

Wednesday PM Room: Johnson-McFarlane
June 21, 2000 Cafeteria

Session Chairs: Robert M. Biefeld, Sandia National Laboratories, Albuquerque, NM 87185-0601 USA; Ishwara Bhat, Rensselaer Polytechnic Institute, Troy, NY 12180 USA

1:20 PM, G1

Dependence of the Background Doping of InAs/(GaIn)Sb IR-Superlattices on MBE Growth Conditions: *Frank Fuchs*¹; L. Burkle¹; J. Schmitz¹; W. Pletschen¹; ¹Fraunhofer Institut für Angewandte Festkörperphysik (IAF), Tullastrasse 72, Freiburg D-79108 Germany

InAs/(GaIn)Sb short-period superlattices (SL) show a broken-gap type II band alignment. The effective band gap can be tailored ranging from the far-IR to the mid-IR wavelength region by changing the In molar fraction of the (GaIn)Sb layers and the individual layer thicknesses. The materials system has gained interest for IR-laser as well as for IR-detection applications. The magneto-transport properties of short-period InAs/(GaIn)Sb superlattices (SLs) grown by molecular beam epitaxy on GaSb substrates are reported. Besides magneto-transport measurements, the characterization of the layers comprises high resolution X-ray diffraction, atomic-force microscopy, infrared photoluminescence (PL), and in-plane photoconductance spectroscopy (PC). For the optimization of the design of low-gap photodiodes the background impurity concentration is a crucial parameter. In the present paper the dependence of the transport properties on the growth parameters is presented. A change from a n-type to p-type conduction of the SLs is observed while increasing the growth temperature from 360 to 440°C. The transport data can be correlated to the PL intensities and the in-plane PC measurements. IR-diodes grown at optimized growth conditions show excellent performance with R_0A products exceeding 1000 Ohmcm² at cut-off wavelengths around 8.5 μm.

1:40 PM, G2

Infrared Light Emitting and Negative Luminescent Devices for Enhanced Thermal Imaging: *Tim Ashley*¹; Richard H. Bennett¹; Geoff R. Nash¹; Graham J. Pryce¹; John A. Haigh¹; Chris L. Jones²; Chris D. Maxey²; ¹DERA, St. Andrews Rd., Malvern, Worcestershire WR14 3PS UK; ²BAE Systems, P.O. Box 217, Millbrook Industrial Estate, Southampton, Hampshire SO15 0EG UK

We describe the use of infrared light emitting and negative luminescent devices to enhance the performance of thermal imaging systems. Infrared negative luminescent devices are simply IR light emitting diodes run backwards to provide an electronic modulation of the infrared emission below the normal, equilibrium background level. The modulation can be almost 100% of the background, therefore the devices can produce photon fluxes equivalent to apparent temperatures of as much as 100°C above or below ambient. The components have two uses in a thermal imager to improve uniformity correction by providing flux references for calibration and to provide a means of radiation shielding without physical cooling. Both will be discussed and experimental result from the former using uncooled indium antimonide based sources to provide fast, multi-point uniformity correction of cryogenic InSb focal plane arrays will be presented. Despite the improvements in uniformity of cryogenic medium and long wavelength focal plane arrays which have been achieved over recent years, all intrinsic infrared arrays require correction of the signal coming off the focal plane before display of an image or analysis by automatic recognition algorithms in order to remove fixed pattern noise arising from the differences in responses of individual pixels. Typically, this is performed by use of a thermo-electric or Peltier device temporarily placed in the optical path to provide a uniform source of photons. These devices have a long response time, taking typically one minute to stabilise, therefore multi-point or frequent correction, which is required in demanding applications with rapidly changing scene tempera-

tures, becomes impossible. The light emitting or negative luminescent device is purely electronic, so its response time is many orders of magnitude faster. By suitable modulation it can provide any flux of photons, either above or below the background level, over a wide apparent temperature range to provide rapid, multi-point correction, so enabling the full sensitivity of each pixel to be utilised. Cryogenic detectors are limited in their sensitivity by variations in the flux of photons from the scene or background, therefore the angle over which the detector receives photons is constrained to that of the scene by a radiation shield. An uncooled negative luminescent device placed external to the cryogenic encapsulation can perform the same function, so simplifying and reducing the size and cost of the encapsulation. We will present results from MWIR negative luminescent devices, made from indium antimonide, which are 3cm² in area and which are used for correction of cryogenic MWIR arrays. The devices are grown by molecular beam epitaxy and their efficiency is maximised by use of integrated optical concentrators. We will also present preliminary results from long wavelength devices made from mercury cadmium telluride grown by MOVPE for use with LWIR systems.

2:00 PM, G3

Epitaxial Lateral Overgrowth of CdTe on Patterned Substrates by MOVPE: *Ruichao Zhang*¹; Ishwara Bhat¹; ¹Rensselaer Polytechnic Institute, ECSE Dept., JEC 6003, 110 8th St., Troy, NY 12180 USA

Infrared detector material, mercury cadmium telluride (Hg_{1-x}Cd_xTe), is generally grown on CdTe substrates because its lattice constant at any x value is closely matched to that of CdTe. As a first step to grow low-defect-density Hg_{1-x}Cd_xTe, high quality CdTe and CdZnTe layers of suitable orientation have to be grown on foreign substrates. Hetero-epitaxial growth of CdTe has been actively studied for the development of large area substrates suitable for Hg_{1-x}Cd_xTe growth. However, rather little is known about the selective growth of CdTe and Hg_{1-x}Cd_xTe on Si and other substrates. Epitaxial Lateral Overgrowth (ELO) is a promising technique to achieve low defect density GaN films on a wide variety of substrates. If ELO can be applied to the hetero-epitaxial growth of CdTe, then low-defect-density CdTe and Hg_{1-x}Cd_xTe films can be grown on lattice-mismatched substrates. ELO of CdTe has been studied using SiN_x mask layer by MOVPE in this work, and selective epitaxy of CdTe has been successfully achieved on different types of patterned substrates. A SiN_x mask layer of about 1000 Å thick was grown on substrates by plasma enhanced CVD. The substrates were patterned by standard photolithography processing. The patterned SiN_x mask layer consists of window strips of different orientations. The CdTe film first nucleates in these window stripes and then grows onto the top of the mask area during an ELO growth. MOVPE of CdTe films on patterned substrates were carried out in a low-pressure vertical quartz MOVPE reactor using metalorganic precursors dimethylcadmium (DMCd) and diethyltelluride (DETe). The deposition temperatures were controlled in the range of 400°C to 550°C and the deposition pressures were between 200 torr to less than 20 torr. Perfect selective growth of CdTe was achieved under different growth conditions. The selectivity and crystal orientation of the films were assessed through scanning electron microscope, single crystal x-ray diffraction and double crystal rocking curves. The vertical-to-horizontal growth rate ratio seem to vary depending on the spacing between the growth windows. The dislocation density in the films is being studied by transmission electron microscope and by etch-pit density measurements. The results will be discussed in detail and be compared with those of the CdTe films grown directly on unpatterned substrates. The growth anisotropy of the CdTe films on different substrates and under different growth conditions will also be discussed. Lateral overgrowth of CdTe with vertical sidewalls on the top of the non-wettable mask area is highly desired for the growth of good quality ELO films. The growth condition and substrate orientation both have a profound effect on the sidewalls of ELO stripes. The obtained favorite growth orientation will be shown for the case of CdTe/Si and GaAs single crystal substrates.

2:20 PM, G4

MBE Growth and High Temperature Performance of HgCdTe Midwave Infrared Detectors: *Terry J. deLyon*¹; John E. Jensen¹; Ichiro Kasai²; J. deBruin²; W. Ahlgren²; G. Venzor²; ¹HRL Laboratories LLC, 3011 Malibu Canyon Rd., Malibu, CA 90265 USA; ²Raytheon Infrared Center of Excellence, 75 Coromar Dr., Goleta, CA 93117 USA

We report on the epitaxial growth and electrical performance of HgCdTe midwave infrared detector structures fabricated by molecular-beam epitaxy. These devices are designed for operation in the 120-160K temperature range with cutoff wavelengths ranging from 3.4-3.8 microns at 140K. The epitaxial structures are conventional p-on-n devices grown at 185°C using CdTe, Te, and Hg sources, with in situ doping using In and As as n and p-type dopants, respectively. Epitaxial structures were designed to examine the impact on device performance of: (1) variation of the n-type baselayer (absorber) thickness, and (2) the inclusion or omission of an underlying wide bandgap buffer layer. Devices were grown with absorber thicknesses of 3, 5 and 7 microns to examine the effect on spectral response characteristics and reverse-bias electrical performance. In addition, five-micron-thick, wide bandgap HgCdTe buffer layers, whose CdTe mole fraction was approximately 0.1 larger than the absorber layer, were introduced into several device structures to study the effect of isolating the device junction from the substrate/epilayer interface. Materials characterization procedures, such as SIMS profiling of alloy composition/dopant distributions and wet chemical defect etching, have been performed to characterize the crystal quality of the epitaxial wafers. The MBE-grown epitaxial wafers were processed into passivated mesa-type discrete device structures and diode mini-arrays using conventional HgCdTe process technology. The details of the electrical characterization of the devices at 120-160K will be presented, including the performance of 25-element diode mini-arrays. Specific electrical performance data to be covered include current-voltage characteristics, spectral response, temperature-dependent R_0A product, and measurements of device quantum efficiency vs. diode area. Highlights of this data include 140K R_0A products in excess of 1×10^6 ohm-cm² at 3.8 microns cutoff for the best devices, which were grown on wide bandgap buffer layers, and which exhibited diffusion-limited performance down to at least 140K. An optimum spectral response characteristic was observed for devices with 5-micron-thick absorbing layers.

2:40 PM, G5

Subpicosecond Spin Relaxation in 3.6-Micron-Band-Gap InAs/GaSb Superlattices: *Thomas F. Boggess*¹; C. Yu¹; J. T. Olesberg¹; Michael E. Flatte¹; W. Lau¹; T. C. Hasenberg¹; E. M. Shaw¹; ¹The University of Iowa, Dept. of Phys. and Astro., 100 IATL, Iowa City, IA 52242 USA

The successful controlled injection of spin-polarized electrons into semiconductors could lead to a variety of new devices, including new magnetic memories and spin-sensitive transistors and diodes. Spin dynamics have also drawn attention due to the broad proposal that physical realizations of quantum computer bits (or qubits) might be achieved in semiconductors using coherent superpositions of carrier spin. Such potential applications have generated intense research activity focused on the injection of spin-polarized currents from ferromagnetic metals or spin filters into semiconductors. InAs-based materials will likely play a critical role in the development of spin-sensitive electronics owing to the large electron mobility that can be realized in these materials and to the presence of a natural surface state that provides a means for contact with metallic materials (including magnetic metals) without a Schottky barrier. While at this stage it is not apparent what device designs will emerge for practical applications, it is clear that progress toward spin-sensitive devices will require the establishment of a firm understanding of the dynamics of spin-polarized carrier populations in these materials. We describe measurements of the spin relaxation rate associated with optically-injected, spin-polarized carriers in an 3.6- μ m-band-gap (300K), InAs/GaSb superlattice. This is an interesting system, not only because of its potential use in various devices, but because of the unique features influencing spin-relaxation in this system. InAs/GaSb interfaces can incorporate both GaAs and InSb bonds, neither of which occurs within the bulk constituents. The presence of these interface-only bonds, and their different spatial orientation in the interface, produces additional spin splitting of the band structure. This splitting can substantially reduce the spin relaxation time of polarized populations. In addition, in these type-II structures, electrons tend to be localized in the InAs layers and holes in the GaSb layers. Hence, spin relaxation through electron-hole exchange interactions may be somewhat suppressed. We note that, to date, there has been no estimate or measure of the spin relaxation time in InAs/GaSb heterostructures. Degenerate pump-probe measurements were performed with 160 fs pulses from an optical parametric oscillator tuned near 3.5 μ m. The pump pulse was circularly polarized to produce a spin-polarized

population, and the differential transmission of the probe was measured for either the same-circular-polarization (SCP) or opposite-circular-polarization (OCP). The OCP signal clearly shows the effects of the growth of the opposite-spin population and the SCP signal shows the decay of the same-spin population. The temporal signatures of these signals indicate a subpicosecond 300K spin relaxation time that is observed to increase with decreasing temperature. We will compare the measured results with theoretical results based on a nonperturbative, fourteen-band, restricted-basis-set calculation for the electronic structure, including spin splitting.

3:00 PM Break

3:40 PM, G6

Spectral Blue Shift and Improved Luminescence Properties with Increasing GaSb Layer Thickness in InAs-GaSb Type-II Superlattices: *Andrew Paul Ongstad*¹; Ron Kaspi¹; Charles E. Moeller¹; Michael L. Tilton²; Donald M. Gianardi²; Joseph Chavez²; Gregory C. Dente³; ¹Air Force Research Laboratory, DELS, 3550 Aberdeen Ave., Albuquerque, NM 87117 USA; ²Boeing Defense & Space Group, P.O. Box 5670, Albuquerque, NM 87185 USA; ³G.C.D. Associates, 2100 Alvarado Dr. NE, Albuquerque, NM 87110 USA

We describe the photoluminescence spectroscopy (PL) and Fourier transform infrared (FTIR) absorbance spectroscopy characterization of a large set of InAs/GaSb type-II strained layer superlattice (SLS) samples. The samples are designed to probe the effect of GaSb layer thickness on the optical properties of the SLS, while the InAs-layer thickness is held fixed. As the GaSb layer thickness is increased, we observe a spectral blue shift of the PL peaks that is accompanied by an increase in intensity, narrower line widths, and a large reduction in the temperature sensitivity of the luminescence. These effects occur despite a significant reduction in the electron-hole wavefunction overlap, and can be attributed to a reduced dispersion in the InAs conduction band as the GaSb layer thickness is increased. In addition, we compare the results of empirical pseudopotential model (EPM) and kp envelop function approximation calculations to the observed blue shift of the primary bandgap. The comparison indicates that the EPM calculations are in better agreement for these samples containing extremely thin layers.

4:00 PM, G7

Temperature Dependence of the Fundamental Band Gaps of GaInAsSb/GaSb and GaSb: *M. Munoz*¹; Fred H. Pollak¹; M. B. Zakia²; N. B. Patel²; J. L. Herrera²; ¹Brooklyn College of CUNY, Phys. Dept. and NY State Ctr. for Adv. Tech. in Ultrafast Photo. Matls. and Appls., Brooklyn, NJ 11210 USA; ²UNICAMP, Lab. de Pesquisa em Dispositivos, IFGW and Centro de Componentes, Campinas, Brazil; ³Universidad de Puebla, Instit. de Fisica, Puebla, Mexico

The quaternary alloy $Ga_{1-x}In_xAs_ySb_{1-y}/GaSb$ is a narrow band gap semiconductor (0.3-0.7 eV) with a number of applications including thermophoto-voltaic cells, infrared light emitting diodes and lasers, photodectors, etc. Using photoreflectance we have measured the temperature dependence (15K-375K) of the fundamental band gaps $[E_0(T)]$ and associated broadening parameters $\Gamma_0^{(T)}$ of two $Ga_{1-x}In_xAs_ySb_{1-y}/GaSb$ samples with compositions of $(x=0.08, y=0.07)$ and $(x=0.07, y=0.05)$ as well as for one GaSb epilayer. All samples were fabricated by Liquid Phase Epitaxy and unintentionally doped. The temperature dependence of $E_0(T)$ and $\Gamma_0(T)$ are significant from both fundamental and applied perspectives. They contain information about the electron-phonon interaction and also are useful in modelling temperature effects in the above devices. We have fit the measured $E_0(T)$ to (a) the semi-empirical Varshni relation: $E_0(T)=E_0(0)-\alpha T^2/(\beta+T)$ where $E_0(0)$ is the band gap at $T=0$ while β and α are the so-called Varshni coefficients, as well as (b) an equation that incorporates the Bose-Einstein occupation factor for phonons: $E_0(T)=E_0(0)-2\alpha_b[\exp(\theta_b T)-1]$ where α_b is the strength of the electron-average phonon interaction and θ_b is an average phonon temperature. The obtained values of β [(4-5) $\times 10^{-4}$ eV/K], β (250K-275K), α_b (27-38 meV), and θ_b (185K-200K) for these samples are typical of most III-V materials. The experimental values of $\Gamma_0(T)$ were fit to a Bose-Einstein-like expression which contains the electron-LO phonon coupling coefficient and LO phonon temperature. Although A. Joulie et al [PR B 23, 928 (1981)] reported $E_0(T)$ of GaSb they did not fit to either Eq. (1) or (2) but to a linear function (-3.5 $\times 10^{-4}$ eV/K), which is valid only at high temperatures. This magnitude is close to our β . Also they did not report $\Gamma_0(T)$.

4:20 PM, G8 +

Growth and Characterization of Sputtered Er₂O₃ Thin Films: Kevin M. Chen¹; Michal Lipson¹; Xiaoman Duan¹; Lionel C. Kimerling¹; ¹Massachusetts Institute of Technology, Depts. of Matls. Sci. and Eng., 77 Massachusetts Ave., Cambridge, MA 02139 USA

Erbium oxide (Er₂O₃) is a promising luminescent material for microphotonic devices because the Er³⁺ f-shell transition is at $\lambda=1.54 \mu\text{m}$ and is temperature independent. Moreover, the concentration of Er³⁺ ions in the oxide is greater by several orders of magnitude over Er-doped systems, thereby enabling access to higher luminescence intensities and light amplification. We have fabricated Er₂O₃ thin films via reactive magnetron sputtering of Er metal in an Ar/O₂ mixture at room temperature. The as-deposited film is amorphous and does not show photoluminescence (PL) because the required ligand field for the Er atoms is absent. An anneal in O₂ is done to crystallize the film, thereby optically activating the Er atoms to yield sharp PL at 4K. Interestingly, in addition to annealing, we have found that Er₂O₃ films which have been deposited and annealed on a film of SiO₂ possess strong PL compared to films deposited directly onto Si; this result has implications on the Er-O-Si phase diagram. In this work, we investigate the relationship between the oxide microstructure and its optical properties. We examine the effect of sputter plasma power and gas pressure, subsequent anneal time/temperature and ambient, and underlying film. Finally, we integrate our understanding of Er₂O₃ film growth to demonstrate a microphotonic device using this material.

4:40 PM, G9 Late News

Session H. Special Topical Session

Wednesday PM Room: Centennial Towers
June 21, 2000 Lounge

Session Chairs: Ben Shanabrook, Naval Research Laboratory, Elect. Sci. and Tech. Div., Washington, DC 20375-5000 USA; Ray Tsui, Motorola, Inc., Tempe, AZ 85284 USA

1:20 PM, H1 *Invited

The Design and Measurement of Molecular Electronic Switches and Memories: M. A. Reed¹; J. Chen¹; A. M. Rawlett²; J. M. Tour²; C. W. Zhou¹; ¹Yale University, Dept. of Elect. Eng., Appl. Phys. and Phys., P.O. Box 208284, New Haven, CT 06520 USA; ²Rice University, Dept. of Chem. and Ctr. for Nano. Sci. and Tech., Mail Stop 222, 6100 Main St., Houston, TX 77005 USA

Investigations of the electronic conduction through conjugated molecules that are end-bound onto surfaces are now possible and have been demonstrated. At best, the electronic properties exhibit simple diode-like behavior that is unsuitable for potential circuit applications. Here we report the observation of large and useful reversible switching behavior in an electronic device that utilizes molecules as the active component. Electronic measurements were performed in a metal top contact (Au)/self-assembled monolayer (SAM) molecule active region/metal bottom contact (Au) embodiment. The essential feature of the fabrication process is the employment of nanoscale device area that gives rise to a small number of self-assembled molecules (ca. 1000) and which eliminates pinhole and other defect mechanisms that hamper through-monolayer electronic transport measurements. The active electronic component was made from 2'-amino-4'-ethynylphenyl-4'-ethynylphenyl-5'-nitro-1-(thioacetyl) benzene. The synthesis of this component commenced with the acylation and nitration of 2,5-dibromoaniline, yielding a nitroacetanilide that underwent Pd/Cu-catalyzed coupling with phenylacetylene preferentially at the more electrophilic C-Br site. Then acetate hydrolysis and coupling with 4-ethynyl(thioacetyl)benzene afforded the desired component. The actual self-assembly process forms the thiolate upon exposure to Au. The I(V) curves of the Au/thiolate/Au devices at 60K show strong negative differential resistance (NDR) characteristics.

The peak current density is $>53 \text{ A/cm}^2$, the NDR is $<-380 \mu\Omega\text{-cm}^2$, and the PVR is 1030:1. The I(V) is fully reversible upon change in bias sweep direction. (A series of control experiments have been done using alkanethiol-derived SAMs, silicon nitride membranes without pores, membranes with pores but without molecules, and SAMs of conjugated molecules similar to the thiolate but not bearing the nitroamine functionalities). The performance exceeds that observed in typical solid state quantum well resonant tunneling heterostructures. The molecule's intrinsic PVR may be considerably larger than that reported here, since the $\sim\text{pA}$ valley currents observed are comparable to typical leakage currents in the silicon nitride. It should be noted that the NDR observation cannot be explained by the Coulomb blockade of interstitial metal particles since two-terminal localized state transport gives rise to current steps and not switching behavior. Two terminal NDR devices have numerous device applications including high frequency oscillators, mixers, multipliers, logic, and in A/D converters; and 3-terminal devices incorporating NDR give rise to interesting novel and compact circuits. New work on the realization of molecular memories will also be presented. This work was supported by DARPA through ONR under grant N00014-99-0406.

1:50 PM, H2 *Invited

Self Assembly of Nanometer-Scale Metallic Wires for Molecular Electronics: Theresa S. Mayer¹; Thomas N. Jackson¹; Christine Keating²; Thomas E. Mallouk²; ¹The Pennsylvania State University, Elect. Matls. and Proc. Rsch. Lab., Dept. of Elect. Eng., University Park, PA 16802 USA; ²The Pennsylvania State University, Elect. Matls. and Proc. Rsch. Lab., Dept. of Chem., University Park, PA 16802 USA

Recent interest in molecular-scale electronics as a means to fabricate extremely dense logic and memory circuits has led to the development of molecular diodes, switches, and negative differential resistance devices. Although these devices may provide the necessary building blocks to continue advancing device integration in step with Moore's law, a molecular-scale interconnect technology is needed to utilize fully their extremely small dimensions. Present photolithographic techniques grow exponentially more expensive with decreasing feature size and may never reach the dimensions required for this new technology. Based on these limitations, it has been suggested that future device integration may be based on alternative approaches that rely on assembly of nanometer-scale colloidal particles such as isotropic and anisotropic metallic particles and carbon nanotubes. In this talk, we will provide a review of recent research activities related to the fabrication and characterization of nanometer-scale metallic wires, and the development of techniques that can be used to assemble these wires into two- and three-dimensional networks. In particular, we are using membrane replication methods to make high aspect ratio, segmented metal wires consisting of alternating layers of Au, Pt, Ag, and Pd that are well suited for orthogonal self-assembly strategies. We have observed using fluorescence microscopy of Au-Pt-Au tipped wires that the Au regions of the rods can be derivatized selectively relative to the Pt with chain-terminating groups such as amines, carboxylates, or single-strand DNA. Using a combination of field- and chemical-assisted assembly techniques, we have aligned and attached 35-200 nm diameter segmented wires with good uniformity and reproducibility onto templated SiO₂ substrates. This has allowed us to characterize electrically simple segmented metal wires as well as more complex wires containing rectifying junctions at the interface between metal layers.

2:20 PM, H3 *Invited

Growth and Properties of Nanotubes: Hongjie Dai¹; ¹Stanford University, Dept. of Chem., Stanford, CA 94305 USA

This talk will present our recent work in controlled synthesis of multi-walled (MWNT) and single-walled nanotubes (SWNT) with ordered architectures. The general growth approach involves chemical vapor deposition on catalyst patterned substrates. Results to be presented include self-oriented MWNTs, individual SWNT wires grown from controlled surface sites, and suspended SWNT architectures with nanotubes directed towards well-defined orientations. It will be shown that the controlled nanotube growth opens up new possibilities in fundamental characterizations and potential applications of nanomaterials. Systematic electron transport measurements are carried out to elucidate the electrical properties of various classes of nanotubes and to study the physics in one-dimensional systems. Functional devices based on individual SWNTs will be shown. Also, our recent work in nanotubes chemical sensors will be presented.

2:50 PM, H4 *Invited

Digital Logic and Switching in a Quantum-dot Cellular Automata

Cell: Gary H. Bernstein¹; Islamshah Amlani¹; Alexei O. Orlov¹; Craig S. Lent¹; Wolfgang Porod¹; Geza Toth¹; James L. Merz¹; Gregory L. Snider¹; ¹University of Notre Dame, Dept. of Elect. Eng., 275 Fitzpatrick Hall, Notre Dame, IN 46556 USA

Fundamental constraints of power dissipation, high electric fields in the drain and gate, and interconnect delays will in the not-too-distant future cause a slowing of the predicted growth of Moore's Law. At Notre Dame, we are investigating a computational paradigm known as quantum-dot cellular automata (QCA) as one possibility of a replacement paradigm for computing which does not rely on power-hungry transistors and relatively slow metal interconnects. Computation with QCA follows the well-understood rules of Boolean logic, but relies on polarization of cells instead of voltages and currents to encode binary data. In QCA, quantum dots are coupled within cells by tunnel junctions, and by Coulomb coupling between cells. Single electrons on the dots are influenced by their neighboring cells, so that the polarization of a given cell indicates a Boolean logical value of 1 or 0. QCA offers many advantages over conventional technology including compatibility with nanostructures, simplified interconnects, and the possibility for extremely high density and speed, and low power dissipation. Although the concept of QCA does not rely on any particular technology, possible ones include quantum dots in semiconductors, metal tunnel junctions, self-assembled dots or, ultimately, molecules. A viable technology will consist of sufficiently small features that can be arranged practically into appropriate patterns over large areas, such as self-aligned structures or molecules. In this work we exploit the metal/tunnel junction system, as it is straightforward to fabricate and robust enough at low temperatures to allow demonstration of the basic principles. The metal-dot system is fabricated using the metal tunnel junction technique pioneered by Fulton and Dolan. In this technique, a double-layer of resist is exposed by electron beam lithography and developed, followed by angled evaporation, in-situ oxidation, and a final angled evaporation to create tunnel junctions. The functional "dots" or "islands" consist of all of the metal that is isolated by tunnel junctions and connected capacitively to neighboring dots and metal-dot single-electron electrometers. These electrometers provide information as to the switching states and energies of the electrons on the dots. The experimental demonstration of functioning cells will be presented. A line of three cells demonstrates that there are no metastable switching states in a line of cells. We will present a QCA majority gate, which is a programmable AND/OR gate and is the basic building block of QCA systems. Progress in pursuing molecular-based QCA systems will also be discussed.

3:20 PM Break

3:40 PM, H5 *Invited

Semiconductor Nanocrystals as Building Blocks for New Materials

Cell: Paul Alivisatos¹; ¹University of California at Berkeley, La Jolla, CA USA

In recent years there have been significant advances in the preparation of semiconductor quantum dots by colloidal chemistry routes. CdSe and InAs are examples of materials which can be made as nanocrystals of high quality. These nanocrystals provide an excellent proving ground for examining size dependent scaling laws of physical properties, and a few examples will be described briefly. Colloidal nanocrystals may also be integrated into more complex structures, and three examples will be described. The first involves blends of nanocrystals semiconductor polymers to yield photovoltaics. A second example involves the integration of single nanocrystals into lithographically prepared transistors. Finally, efforts to use DNA to create complex spatial arrangements of nanocrystals will be described.

4:10 PM, H6 *Invited

Stress-Engineered Epitaxial Quantum Nanostructures

Cell: A. Madhukar¹; ¹University of Southern California, Depts. of Matls. Sci. and Phys., Los Angeles, CA 90089-0241 USA

Epitaxial semiconductor nanostructures formed via growth control have, over more than a decade, provided the means for examining physical phenomena in low (zero and one) dimensions as well as exploring quantum box and wire based electronic and optoelectronic devices. Of these, coherent three-dimensional islands formed during strained epitaxy constitute the most successful class of semiconductor quantum dots (QD) to date. In this talk we will focus on the role of surface and subsurface

stress and its innovative manipulation for controlling the size, shape, density, and spatial location of such quantum dots. The InAs/GaAs(001) combination is used as the prototypical experimental vehicle and the Ge/Si as a model system for simulations of the stress distribution. Extremely narrow photoluminescence (PL) linewidths (<20meV) realized even for the as-grown InAs/GaAs QD inhomogeneous size distribution have allowed temperature and incident power dependent optical spectroscopy, in conjunction with structural information, to yield size-dependent electronic structure and, for the first time, the size-dependent exciton-phonon coupling strength. The lattermost is of central importance to carrier relaxation and hence devices ranging from lasers to photodetectors. This work reported has been carried out in collaboration with I.Mukhametzhanov, R. Heitz, M. Makeev, Z. Chen, O. Baklenov, and E. Kim. It is supported by the MURI program through AFOSR.

4:40 PM, H7 *Invited

Quantum Dot Based Semiconductor Laser Diodes

Cell: Marius Grundmann¹; ¹Technische Universität Berlin, Hardenbergstr. 36, Berlin D-10623 Germany

We report about the progress in semiconductor laser diodes made by employing nano-crystalline active media containing quantum dots. We focus on three device types, 1300 nm lasers on GaAs substrate, high optical output lasers, and mid/far-infrared emission and their theoretical description. A particular advantage of QD lasers is the possibility to reach emission wavelengths that are larger than those obtainable with quantum wells of the same material system. We will present InGaAs/GaAs QD lasers emitting at 1300 nm showing superior characteristics compared to InP-based devices regarding the threshold current and temperature stability. Model calculations are presented for different quantum dot geometries such as seeded quantum dots and quantum dots in a strained quantum well. High power semiconductor laser diodes based on multiple InGaAs/GaAs quantum dot layers grown by metal-organic chemical vapor deposition are demonstrated. Due to reduced carrier diffusion decreased non-radiative surface recombination and facet overheating and higher catastrophic optical damage (COD) threshold are expected. Also the realization of new lasing wavelengths is possible. The devices exhibit a peak power of more than 4 W at 940 nm, >3.5 W at 1100 nm and 2.7 W at 1300 nm. The development of the lasing spectrum under high injection current is modeled theoretically describing the dynamics using master equations for the micro-states (MEM). The use of quantum dots for creating lasers in the mid- and far-infrared spectral range based on inter-sublevel transitions is explored. We report the electrically pumped emission of mid-infrared (MIR) radiation from bipolar quantum dot lasers during near-infrared (NIR) lasing. The MIR spectrum exhibits a peak at 16 μm and is dominantly TM polarized. The MIR intensity exhibits a super-linear dependence on the injection; a maximum MIR power of 0.1 μW per facet was realized. Such devices are also modeled theoretically using MEM. Conditions for MIR lasing are predicted. Besides the necessary inversion population for the electron ground and excited states, it is important to avoid NIR lasing on the excited state. This work has been carried out in collaboration with D. Bimberg, A.R. Kovsh, N.N. Ledentsov, D.A. Livshits, C. Ribbat, R. Sellin, Y.M. Shernyakov, V.M. Ustinov, A. Weber, and A.E. Zhukov. The work has been supported by bmb+f (13N7231/7 and NanOp (<http://www.nanop.de>)), DFG in the framework of Sfb 296 and Gr1011/7-1, and INTAS (97-751, 96-0467).

5:10 PM, H8 *Invited

Optically Probing and Controlling Single GaAs Quantum Dots

Cell: Daniel Gammon¹; ¹Naval Research Laboratory, Washington, DC USA

Recently it has become possible to probe individual excitons localized laterally in narrow GaAs quantum wells using high spatial and spectral resolution optical techniques. Discrete, atomic-like spectra with homogeneously broadened linewidths as narrow as a few tens of micro-eV have been measured. These linewidths are two orders of magnitude narrower than the ensemble linewidth arising from inhomogeneous broadening and an order of magnitude narrower than the narrowest observed in wide quantum well samples. This extraordinary reduction in linewidth can be explained in part by the removal of inhomogeneous broadening accomplished by probing individual localized excitons, and in part by the reduction in homogeneous linewidth in going from 2D to 0D. This great reduction in linewidth attained in PL by probing individual QDs has led to a number of new observations including fine structure splittings, hyperfine structure splittings and the measurement of the nonlinear response

of a single quantum dot. Using coherent picosecond pulses, coherent control and the generation of superposition states have been demonstrated. These examples of coherent spectroscopies on individual excitons are first steps toward what may lead eventually in its maturity to coherent optical control of QDs analogous to what is now possible in atoms. Such techniques would be part of a "quantum toolbox" that could enable such revolutionary applications such as quantum computation using quantum dots.

Session I. Advanced Nitride Epitaxy

Wednesday PM Room: Lindsey Auditorium
June 21, 2000 Location: Sturm Hall

Session Chairs: Tom Myers, West Virginia University, Phys. Dept., Morgantown, WV 26506 USA; Russell D. Dupuis, The University of Texas-Austin, Austin, TX 78712 USA

1:20 PM, I1

Gallium Nitride Epitaxial Lateral Overgrowth Kinetics: *Christine C. Willan*¹; Michael E. Coltrin¹; Michael E. Bartram¹; Jung Han¹; ¹Sandia National Laboratories, Dept. 1126, P.O. Box 5800, MS 0601, Albuquerque, NM 87185-0601 USA

Gallium nitride is a wide bandgap semiconductor with a broad range of potential applications. GaN thin films usually contain a high defect density, leading to poor device performance. Epitaxial Lateral Overgrowth (ELO) has been shown to dramatically reduce defect densities, often by 2 orders of magnitude or more. We are conducting fundamental studies of GaN crystal growth kinetics during ELO. In ELO, a mask pattern of dielectric material, for example silicon nitride, is deposited on top of a GaN buffer layer. Further growth of GaN occurs selectively on exposed areas of the underlying buffer layer, and not on the dielectric material. Many coupled phenomena potentially contribute to observed ELO behavior, including mass transport, anisotropic growth kinetics, and thermodynamics. We have designed a custom mask to examine ELO growth kinetics over a wide range of patterning dimensions. Cross-sectional areas of grown features are obtained by scanning electron microscopy (SEM), and are used to study growth kinetics. Over multiple growths at various conditions a wide range of apparent growth kinetics are observed, and a way of systematizing the data must be found. The on exposed regions depends strongly on the mask pattern, i.e., the size of the exposed window opening (W) and the pitch (P), the repeat distance of the pattern. Because growth does not occur on masked areas, a growth rate enhancement is observed on the unmasked regions due to lateral mass transport. Experimental data shows that the lateral transport of material has near-unit efficiency. Thus, the cross-sectional area A_i of a feature is expected to increase linearly with the pattern pitch P_i . In the simplest model, A_i is expected to be proportional to the (unmasked) growth rate, G_o , and the deposition time, t . We propose that features of differing size are self-similar when the proper length scale is used, which we recognize as the exposed window size, W_i . Our new ELO theory predicts that scaled area a_i (defined as A_i/W_i^2) should equal $G_o * P_i * t / W_i^2$, which we define as a dimensionless growth time τ_i . Thus, a plot of a_i vs τ_i should yield a straight line. We have found a quantitative way to translate results from different pattern dimensions into a pseudo time basis τ_i by scaling growth features by the length scale W_i . This allows us to study a wide range of growth kinetics from multiple growth runs with varying pattern dimensions in a "combinatorial" manner. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

1:40 PM, I2

Lateral Overgrowth of GaN on SiC Substrates with Vertically Conducting Buffers: *Q. Fareed*¹; Vinod Adivarahan¹; J. Zhang¹; M. Asif Khan¹; J. W. Yang¹; G. Simin¹; R. Gaska²; M. Shur³; ¹University of

South Carolina, Dept. of Elect. and Comp. Eng., 301 S. Main St., Rm. 3A80, Columbia, SC 29208 USA; ²Sensor Electronic Technology, Inc., 21 Cavalier Way, Latham, NY 12110 USA; ³Rensselaer Polytechnic Institute, Dept. of ECSE and CIEEM, Troy, NY 12180 USA

The epitaxial lateral overgrowth (ELO) technique allows to deposit GaN layers with defect densities well below 10^6 cm⁻² and to dramatically improve the performance and lifetime of light-emitting devices. Several groups to date have reported the deposition of GaN/InGaN MQW light emission devices over conducting SiC substrates with vertically conducting buffer layers. The combination of ELOG with vertically conducting buffers on conducting SiC should provide the following advantages: (i) high quality of ELOG material; (ii) simplified LED/laser diode processing; (iii) significantly better thermal management. To date, ELOG growth on SiC substrates has only been reported by Dr. B. Davis et al. at NC State. However, their structures were grown using insulating AlN buffer layer. In this paper we report, for the first time, the lateral overgrowth of GaN on conducting 6H-SiC substrates with vertically conducting buffer layers by metalorganic chemical vapor deposition (MOCVD). Epitaxial lateral overgrowth of GaN has been carried out on 1.5 μ m thick GaN template. PECVD deposited 150 nm thick SiO₂ stripes aligned in the <1100> direction served as ELOG mask. The window and stripe widths varied from 3 to 25 μ m. Complete coalescence of the ELOG growth fronts was achieved for growth temperatures below 1000°C. The coalescence was observed within 8 μ m thick ELOG films. The structural and optical properties of the vertically conducting ELOG films were studied using cross-sectional SEM, AFM and photoluminescence. We will also present the detail measurements of vertical transport in ELOG and conventional GaN and GaN/InGaN MQW structures on conducting SiC with vertically conducting buffers.

2:00 PM, I3

Hydrogen-Induced Changes in the Epitaxial Lateral Overgrowth of GaN: S. Gu¹; L. Zhang¹; R. Zhang²; *T. F. Kuech*¹; ¹University of Wisconsin, Dept. Chem. Eng., 1415 Engineering Dr., Madison, WI 53706 USA; ²Nanjing University, Dept. of Phys., Nanjing 210093 PRC

Epitaxial Lateral Overgrowth (ELO) has been widely applied in the growth of high quality GaN materials by Hydride VPE (HVPE). The structure and properties of ELO materials are dependent on many growth and procedural factors. The detailed aspects of the growth chemistry, at the ELO growth front, are not well understood but do affect the facet formation and growth kinetics. We have studied hydrogen addition to the growth ambient as well as very narrow mask openings as means to influence the growth behavior. The use of narrow stripe openings enables the lateral growth process to be dominated by the kinetics of growth on the facets shortly after the initiation of growth. Hydrogen can shift the local equilibrium in the HVPE system and provide additional reaction pathways for chlorine removal from the growth front. MOVPE-grown GaN layers were patterned using either x-ray or photolithography to possess strips, aligned in (11 $\bar{2}$ 0) direction, over broad areas with openings in the SiN_x mask of 0.5-5 μ m separated by 10-20 μ m masked regions. Vertical and triangularly shaped ELO regions can be grown by HVPE with a N₂ carrier gas by changing the growth conditions. The addition of hydrogen to the growth ambient results in only triangular growth regions until coalescence. This stable initial facet, previously reported by Usui et al. (Jpn. J. Appl. Phys., 36, L899 (1997)), present when hydrogen used as carrier gas, changes little with growth conditions and mask geometry (NH₃ partial pressure, growth rate, or pattern space size). Hydrogen addition substantially improves the GaN surface morphology and materials properties. While differences in materials properties change a great deal with the specific growth conditions, H₂ addition always yielded narrower x-ray linewidths for films grow at the same rate and to the same thickness, i.e. the FWHM of the (0002) reflection varied from 450 arcsec to 350 arcsec for 10 μ m thick GaN, for N₂ and N₂/H₂-based growth, respectively. Corresponding growth measurements on broad area (non-patterned) substrate exhibit an increase of the growth rate with NH₃ partial pressure in the reactor when using N₂/H₂. This dependence on the NH₃ partial pressure, not seen in the N₂-only case, indicates that analogous changes in the growth chemistry are occurring on this facet as well. An enhanced Ga-atom mobility can result from the removal of growth reaction products from the facet, increasing diffusion and growth rates and leading to a smoother growth surfaces. The detailed impact of hydrogen addition on the materials properties, such as x-ray linewidth, photoluminescence and surface morphology, will be presented for both coa-

lesced and non-coalesced ELO GaN and the underlying chemical mechanisms proposed that give rise to these changes.

2:20 PM, I4

Lateral Epitaxial Overgrowth of GaN by Pulsed-MOCVD: *J. Yang*¹; Q. Fareed¹; V. Adivarahan¹; J. Zhang¹; M. Asif Khan¹; G. Simin¹; R. Gaska²; M. Shur²; ¹University of South Carolina, Dept. of ECE, 301 S. Main. St., Rm. 3A80, Columbia, SC 29208 USA; ²Sensor Electronic Technology, Inc., 21 Cavalier Way, Latham, NY 12110 USA

Epitaxial lateral overgrowth (ELOG) technique has been widely used to grow low dislocation density GaN epitaxial layers to improve the performance and lifetime of optoelectronic devices. So far, GaN lateral overgrowth has been carried out using conventional MOCVD and HVPE techniques with growth temperatures in excess of 1050°C. The emphasis has been made over increasing the lateral to vertical growth rates (LTVG) ratio to reduce the ELOG layer thickness required for complete coalescence. This requires the use of high growth temperatures and low ammonia flows resulting conducting GaN layer. In this paper we for the first time report a new pulsed-MOCVD approach capable of high LTVG ratios at growth temperatures as low as 950°C. Our approach can potentially reduce the dopant incorporation resulting from the high growth temperatures and the ELOG masking materials. Epitaxial lateral overgrowth of GaN was carried out on 1.5 μm thick GaN grown by MOCVD GaN with conducting buffer layer on n-type 6H-SiC substrates. PECVD deposited 150 nm thick SiO₂ stripes aligned in the <1100> direction served as ELOG mask. The initial seed layers were grown using conventional MOCVD method. The grown samples have two types of facets ({1120} and {1101}) besides the flat (0001) top facet in the lateral overgrown area depending upon the growth conditions. Pulsed MOCVD growth was then carried out at 940-1000°C with TEGa and NH₃ as the precursors. TEGa was kept on all the time while ammonia supply was pulsed ON and OFF for 5 and 3 seconds each cycle respectively. These conditions resulted in an LTVG ratio of 2 for a 950°C growth temperature. Using this pulsed MOCVD process we were able to obtain high quality coalesced ELOG layers. AFM, SEM and PL measurements were used to study the structural and optical properties of the samples. Some initial performance results of vertically conducting light emitting devices fabricated on pulsed MOCVD grown ELOG GaN epitaxial layers will also be presented.

2:40 PM, I5 +

Direct Lateral Epitaxy Overgrowth of GaN on Sapphire Substrate Based on Sparse GaN Nucleation Technique: *Xingang Zhang*¹; P. D. Dapkus¹; Ruijuan R. Li¹; D. H. Rich¹; ¹University of Southern California, Matls. Sci. Dept., 3651 Watt Way, VHE 313, Los Angeles, CA 90089 USA

Low temperature buffers layers (LTB) are always used to grow high quality GaN on sapphire, SiC or Si substrates to overcome the thermal lattice and thermal mismatches. However, the high density of nucleation grains from LTB also produce a high density of dislocations (10^8 - 10^{10} cm⁻²) because of the tilt and twist between these grains. Although blue LEDs and laser diodes (LD) have been demonstrated on these highly defective GaN thin films, LD with lifetime longer than 10,000 hours can be achieved only when the materials defect density was reduced to 10⁴ cm⁻² by lateral epitaxy overgrowth (LEO). Besides LEO, another possible way to reduce defect density is to reduce the nucleation density and therefore reduce the grain boundary density of as-grown GaN film. Our recent metalorganic chemical vapor deposition (MOCVD) growth studies showed that using special surface treatment, very thin GaN low temperature buffer layer of 5 nm, slow ramping up to the growth temperature, and appropriate V/III ratio, a GaN low temperature buffer with nuclei density as low as 4 x 10⁴ cm⁻² can be attained on sapphire substrates (sparse nucleation). The average distance between each nuclei is around 40 μm. In order to control the nucleation sites, we further precede our growth on sapphire substrates with stripe patterning (2-5 μm opening, 10-40 μm periodicity) along either <1100> or <1120> using SiO₂ or SiN_x as mask materials. Conventional photolithography, dry or wet etching were used to form the stripe patterns and expose the sapphire substrate. Using our sparse nucleation technique, the nuclei sites can only grow in the stripe opening regions (sapphire surface exposed). GaN LEO was then performed at 1060°C. The GaN hexagonal plates originating from these nucleation sites are well aligned inside the mask opening regions. These GaN plates coalesce with each other forming the stripes. The stripes then grow laterally until they coalesced with other neighboring stripes. The cathodoluminescence

(CL) image shows strong and uniform band gap luminescence from GaN thin film from the lateral overgrown region. AFM studies show no threading dislocations in the LEO GaN and also show the existence of widely separated atomic steps on the surface. The effects of MOCVD growth conditions on the microstructure, morphology, optical properties of LEO GaN studied by AFM, SEM, CL Imaging and X-ray Diffraction. Our studies demonstrate a new and much simplified LEO technique to improve the GaN optical and structural qualities that may impact future growth design and device fabrication of III-nitride materials.

3:00 PM Break

3:40 PM, I6

Cantilever Epitaxy on Textured Substrates: A Simple Two-Step Approach to Low-Defect-Density GaN Substrates: *Carol I.H. Ashby*¹; Christine C. Willan¹; Paula P. Provencio¹; Nancy A. Missert¹; David M. Follstaedt¹; Gregory M. Peake¹; Jung Han¹; ¹Sandia National Laboratories, P.O. Box 5800, MS 0603, Albuquerque, NM 87185-0603 USA

A continuing problem for the realization of high-performance microelectronic and optoelectronic devices in III-N materials systems has been the absence of an inexpensive substrate that would permit the growth of low-defect-density epitaxial nitride structures. Epitaxial lateral overgrowth (ELO) and pendeopitaxy (PE) have been employed to produce localized regions of lower defect density (<10⁷ threading dislocations (TDs)/cm² or effectively "TD-free"). Both of these processes employ multiple steps: growth of III-nitride on a conventional planar substrate, deposition of a dielectric masking layer (ELO), photoresist patterning to define growth windows in the dielectric (ELO) or to define mesas on the III-nitride (PE), etching of the dielectric window (ELO) or III-nitride mesa (PE), and regrowth of III-nitride in the vertical and lateral directions. Although the laterally grown regions exhibit greatly reduced TD densities, the window and mesa regions retain the very high TD density of the original planar nitride layer. Our new process of cantilever epitaxy (CE) using textured substrates is a simple, two-step process that produces "TD-free" material in the cantilevers and markedly reduces the TD density over the support regions. The two steps consist of 1) etching small-area features in a conventional substrate (sapphire, SiC, or Si), and 2) growing a coalesced film of III-nitride. Initial efforts have employed 2.5- to 3.8-μm-wide support lines etched in sapphire parallel to the {112̄0} planes. A single growth of GaN at variable temperatures has produced coalesced GaN cantilever surfaces spanning up to 9-μm-wide trenches with a 0.1 degree tilt, as measured by atomic force microscopy (AFM). Transmission electron microscopy (TEM) and AFM characterization of the cantilever regions show no evidence of TDs penetrating the cantilevers and few TDs at their coalesced interface. AFM and TEM studies have further shown pronounced reductions of TDs directly over the support within up to 1 μm from the support edge. Cathodoluminescence (CL) measurements have shown only a 25% difference in CL intensity for the cantilever vs. support regions. The periodicity in CL intensity is consistent with the TD density estimates made by AFM and TEM, i.e. the darker regions corresponding to films grown on the support structures are 2 μm narrower than the physical width of the support, suggesting a reduction in TD density on the support surface within 1 μm of the support. Further experiments are in progress using reduced-area substrate textures designed to minimize TD formation in the support region. The degree to which "dislocation-free" material can be grown on these improved substrates will also be discussed. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

4:00 PM, I7

The Influence of Growth Parameters on Grain Size and Electrical Properties in GaN Films: *Mark E. Twigg*¹; Daniel D. Koleske¹; Alma E. Wickenden¹; Richard L. Henry¹; Mohammad Fatemi¹; ¹Naval Research Laboratory, Code 6812, 4555 Overlook Ave., S.W., Washington, DC 20375 USA

The control of grain size is an important problem in heteroepitaxial MOVPE growth of GaN on sapphire. As we have determined by XTEM observations, grain size can be increased by choosing growth conditions that slow grain growth, such as reduced alkyl flow rates and greater reactor pressure. We have studied GaN growth in two different MOVPE reactors: a conventional vertical (CV) reactor as well as a close-spaced showerhead (CSS) reactor. Larger grain size in GaN films grown in the CV

reactor can be achieved by increasing hydrogen as well as by reducing alkyl flow. Conventional growth conditions for the CV reactor are a pressure of 250 torr with flow rates of 15 sccm for the alkyl, 5 l/min for hydrogen, and 3 l/min for ammonia. Decreasing the alkyl flow to 8 sccm while increasing the hydrogen flow to 10 l/min results in 5 micron grains, as compared with 1 micron grains under conventional growth conditions, as well as higher mobility (700 cm²/Vs) than for the smaller grained film (300 cm²/Vs). In addition to increasing grain size, higher reactor pressure (i.e. increasing proportionately the partial pressures of alkyl, hydrogen, and ammonia) enhances the probability that hydrogen reacts with surface carbon to form methane. Thus, increasing the CV reactor pressure from 39 to 130 torr is also seen to reduce the carbon concentration from 3E17/cm² to 8E16/cm² in the GaN film, as we have verified by SIMS measurements. Reducing the carbon concentration corresponds with decreases in film resistivity, suggesting that carbon acts a compensating dopant. The conflicting FET and HEMT device requirements of both high resistivity and high mobility, however, are rarely met at a single reactor pressure. A solution to this dilemma is to maintain on the first stage of high temperature GaN growth at a higher pressure, in order to establish a larger grain size. Once this grain size has been established, the pressure is dropped to a level where a higher carbon concentration can be maintained. Our XTEM and SIMS measurements indicate that by following 250 torr initial growth with 49 torr final growth, large-grained (1 micron) films can be grown in the CV reactor with higher carbon concentration (2E17/cm²). In the CSS reactor, Si-doped GaN films grown at 200 torr are seen to have lower mobilities (300 cm²/Vs) than for films grown at 130 torr (400 cm²/Vs), although both films consist of large (2-5 micron) grains. Pressure above 130 torr appear to give rise to grain misorientation attributable to island faceting with the resulting formation of twist boundaries. This contention is supported by x-ray diffraction measurements, as well as by XTEM observations.

4:20 PM, I8

Heteroepitaxy of GaN on H-Etched SiC: C. D. Lee¹; V. Ramachandran¹; R. M. Feenstra¹; W. L. Sarney²; L. Salamanca-Riba²; D. C. Look³; W. J. Choyke⁴; R. P. Devaty⁴; D. W. Greve⁵; ¹Carnegie Mellon University, Phys. Dept., Pittsburgh, PA 15213 USA; ²University of Maryland, Dept. Matls. and Nuc. Eng., College Park, MD 20742 USA; ³Wright State University, Semiconduct. Rsch. Ctr., Dayton, OH 45435 USA; ⁴University of Pittsburgh, Dept. Phys. and Astro., Pittsburgh, PA 15260 USA; ⁵Carnegie Mellon University, Dept. Elect. and Comp. Eng., Pittsburgh, PA 15213 USA

The structural, electronic, and optical properties of Ga-polar GaN grown by plasma-assisted molecular beam epitaxy (MBE) on SiC(0001) have been studied. Si-face SiC is used, both 4H and 6H polytypes, and the surface is H-etched at 1600°C in a H atmosphere to remove polishing damage. Prior to growth, Si is deposited on the surface and it is heated to 1000°C to obtain a $\sqrt{3}\times\sqrt{3}$ reconstruction. Growth is performed at 700-750°C, using an RF-plasma source for N, and with Ga flux greater than the N flux. Good structural quality is obtained for the films: triple-axis x-ray lines widths of about 0.5 arcmin for both ω and ω -2 θ scans of the (0002) reflection, and 2-3 arcmin for the (11-24) reflection. Threading dislocation densities as low as 2×10^8 cm⁻² are observed by transmission electron microscopy (TEM) for the highest growth temperatures, and almost all of the threading dislocations have edge character. X-ray studies and TEM also reveal the very substantial improvement in structural quality arising from the H-etching procedure. Flat morphology, revealing atomic steps on the surface, is obtained only for very Ga-rich conditions (Ga/N flux ratio \cong 2). However, these Ga-rich conditions are also believed to result in the relatively high background carrier concentration of 8×10^{17} cm⁻³ as well as deep level emission near 2.8 eV seen in low-temperature photoluminescence. For lower Ga fluxes, the structural quality of the films remains high, although the surface morphology develops pits and trenches, associated with preferential evaporation of material near dislocations during growth. Electrical and optical characterization of these films grown with reduced Ga flux rates are in progress and will be reported. Also, a comparison will be made between our results with those of other groups using both plasma-assisted and reactive (with ammonia) MBE. This work was supported by the Office of Naval Research and the Air Force Office of Scientific Research.

4:40 PM, I9

MOCVD Regrowth of GaN on Free-Standing GaN Substrate Prepared by Hydride Vapor Phase Epitaxy: Ig-Hyeon Kim¹; Jae-Yong Han¹; Sung-Su Park¹; Jae-Yeol Lee¹; Sung-Kuk Lee¹; Jae-Won Lee¹; ¹Samsung Advanced Institute of Tehchnology, Comp. Semiconduct. Lab., P.O. Box 111, Suwon, Korea

GaN overlayers were grown on free-standing HVPE (Hydride Vapor Phase Epitaxy) GaN substrate by metalorganic chemical vapor deposition. Surface morphology of GaN overlayer was investigated with various surface treatment processes including mechanical polishing, chemical assisted ion beam etching (CAIBE), and thermal annealing. It was found that ion beam etching process on polished free-standing GaN substrate is essential to grow high quality GaN with the defect density of about 10⁶ cm⁻². Epi-grade surface morphology was obtained on the optimized condition of surface treatment. The ion beam etching About 2000 Å in depth can completely remove the surface damages caused by mechanical polishing and results in epi-grade surface of GaN overlayer. There exist an optimum conditions for ion beam etching to obtain high quality GaN overlayer with smooth surface. Excessive ion beam etching over the optimum value would rather create damages on the surface by the energetic ion bombardment. The performance of LEDs grown on both substrates of Sapphire and free-standing GaN was investigated and discussed in terms of surface morphology and defects density.

5:00 PM, I10 +

Gas Phase Chemistry of Metalorganic and Nitrogen-Bearing Compounds used in Gallium Nitride Growth: Ramchandra Wate¹; J. A. Dumesic¹; T. F. Kuech¹; ¹University of Wisconsin, Dept. of Chem. Eng., 1415 Engineering Dr., Madison, WI 53706 USA

The growth of GaN and related materials is complicated by gas phase reactions not typically found in the metal organic vapor phase epitaxy of other III-V materials. The most well known reaction is the formation of a gas phase adduct between trimethyl gallium, (CH₃)₃Ga, and ammonia, NH₃, that readily leads to the formation of more complex gas phase products, such as (CH₃)₂GaNH₂_{x=2 or 3}, which further react and complicate the detailed growth behavior. The presence of other gas phase nitrogen compounds can modify these reactions. The addition of trimethyl amine to the gas phase, (CH₃)₃N, can lead to a suppression of this rapid adduct formation and oligomerization, thereby in principle simplifying the growth behavior and reactor design. Trimethylamine and trimethyl gallium in hydrogen do not participate in such high temperature reactions. The combined pyrolysis of (CH₃)₃Ga and (CH₃)₃N, appear to follow independent decomposition pathways. The detailed mechanisms responsible for the observed gas phase reactions were investigated by density functional theory (DFT) calculations, performed with Gaussian98 software. The chosen DFT method uses a hybrid method employing Becke's three-parameter approach, B3LYP. These calculations initially determined the heat of reaction for the overall reaction as well as the elementary steps. The overall reaction involves the ammonia adduct formation followed by the elimination of methane. This is described by an intramolecular pathway for the formation of CH₄ from the (CH₃)₃Ga:NH₃ adduct, in which a hydrogen atom is transferred from ammonia to a methyl group. The activation barrier for the formation of this activated complex is 36 kcal/mol. A second step involves the reaction of (CH₃)₂Ga:NH₂ with trimethyl gallium to form a second adduct, (CH₃)₂Ga:NH₂:Ga(CH₃)₃, in which the NH₂ group bridges between two Ga atoms. This adduct then binds NH₃ and leads to the formation of CH₄ and the ((CH₃)₂Ga:NH₂)₂ dimer by intramolecular transfer of a hydrogen atom from NH₃ to a methyl group. The activation energy for this intramolecular reaction is 21 kcal/mol. The interaction of (CH₃)₃N with the (CH₃)₃Ga and (CH₃)₂GaNH₂ molecules was also calculated and was found to be very similar to the interaction of ammonia with these molecules. The simple blocking of the methane elimination reaction by trimethyl amine through the preferential formation of a (CH₃)₃Ga-(CH₃)₃N adduct is therefore not the underlying mechanism for the suppression of the (CH₃)₃Ga-NH₃ based methane elimination reaction seen in our experimental data with the introduction of (CH₃)₃N to the gas phase. These results indicate a more complex set of gas phase processes, such as involvement of the (CH₃)₂Ga:NH₂:Ga(CH₃)₃ adduct in the formation of CH₄. We will present both these experimental findings as well as the quantum chemistry calculations highlighting the reaction pathways of these species important in the growth of GaN and related materials.

Session J. Contacts to GaN and Other Wide Bandgap Semiconductors

Wednesday PM Room: Driscoll Center
June 21, 2000 North - Pub

Session Chairs: Leonard Brillson, The Ohio State University, Columbus, OH 43210 USA; Suzanne Mohney, The Pennsylvania State University, Matls. Sci. and Eng. Depts., University Park, PA 16802 USA

1:20 PM, J1 +

Characterization of Ti/Pt/Au Ohmic Contacts on p-type GaN: *L. Zhou*¹; F. A. Khan¹; W. Lanford¹; J. Han²; J. -W. Yang³; M. A. Khan³; I. Adesida¹; ¹kMicroelectronics Laboratory, Dept. of Elect. and Comp. Eng., 128 N. Wright St., Urbana, IL 61801 USA; ²Sandia National Laboratories, Albuquerque, NM 87185 USA; ³University of South Carolina, Columbia, SC 29208 USA

Low resistance ohmic contacts on p-type GaN is of great importance in the fabrication of optoelectronic devices based on GaN. So far, only three ohmic metallization processes have been reported on moderately doped p-GaN that have achieved specific contact resistances (R_c) on the order of $10^{-5} \Omega\text{-cm}^2$. One of these methods uses Ta/Ti bilayer contacts and requires a post-deposition anneal of 20 minutes at 800°C to achieve $R_c = 3 \times 10^{-5} \Omega\text{-cm}^2$. However, this contact is unstable in air. Another low-resistance contact scheme, which is capable of achieving a R_c as low as $4 \times 10^{-6} \Omega\text{-cm}^2$, requires deliberate oxidation of the Ni/Au contacts at 500°C for 10 minutes. Such an oxidizing anneal may be incompatible with conventional device processing steps. The temperature stability of the unannealed Pt contacts fabricated using the third method, which uses a two-step etching process and demonstrated $R_c = 2 \times 10^{-5} \Omega\text{-cm}^2$, is still unknown. Metal-GaN interface studies have revealed that a surface oxide layer is directly correlated with increased metal-semiconductor barrier heights for metal contacts on p-GaN. The existence of this insulating layer partially explains why attempts at directly depositing metals with high work function on p-GaN have not been very successful in obtaining low-resistance ohmic contacts. Since titanium has been used to reduce surface oxides on semiconductors such as GaAs, using Ti as the first layer in a metallization for ohmic contacts on p-type GaN may be beneficial. In this paper, we report low-resistance ohmic contacts achieved using Ti/Pt/Au and Ti/Pd/Au metallizations on p-type GaN. Ti/Pt/Au contacts with different initial layer (Ti) thicknesses were studied. We found that the optimum thickness of Ti depends on the surface treatment prior to metal deposition, suggesting that the best Ti/Pt/Au contact has a layer of titanium that is close to being completely consumed in reducing the surface oxide. The best contacts with conventional HF:DI surface treatment exhibited a R_c of $4.2 \times 10^{-5} \Omega\text{-cm}^2$ and contact resistivity of $21 \Omega\text{-mm}$, achieved after annealing a Ti (15nm)/Pt(50nm)/Au (80nm) contact at 800°C for 2 minutes. The effect on R_c by other surface treatments, including a two-step surface etch (buffered oxide etch followed by $[\text{NH}_4]_2\text{S}$) and a KOH surface tech, will also be reported. For high temperature applications, highly stable contacts are desired. Therefore, the effect of high temperature annealing and extended thermal treatment on the performance of Ti/Pt/Au contacts will be reported.

1:40 PM, J2 +

Evidence of Band and Bending at the Surface of p-type GaN Measured by Synchrotron Radiation Photoemission Spectroscopy: *Jong Kyu Kim*¹; Jae Won Lee²; Yong Jo Park²; Taeil Kim²; Ki-jeong Kim³; Bongsoo Kim³; Seong Wook Ryu¹; Changmin Jeon¹; Sang Youn Han¹; Yu-Hwa Cho¹; Jung Ho Je¹; Jong-Lam Lee¹; ¹Pohang University of Science and Technology, Matls. Sci. and Eng. Dept., San 31 Hyoja-Dong, Pohang, Kyungbuk 790-784 South Korea; ²Samsung Advanced Institute of Technology (SAIT), Photo. Lab., Suwon, Kyunggi-do 440-600 South Korea; ³Pohang University of Science and Technology, Beamline Rsch. Div., San

31 Hyoja Dong, Pohang Accel. Lab., Pohang, Kyungbuk 790-784 South Korea

Many attempts have been conducted to find a way of lowering the contact resistivity for p-type GaN. It was reported that the surface treatment using boiling aqua regia was effective to reduce the contact resistivity by three orders of magnitude. However, the origin of the reduction of contact resistivity by the surface treatment is still unknown. In the present work, we measured the band bending at the surface of p-type GaN with surface treatments using synchrotron radiation photoemission spectroscopy. The p-type GaN films ($p = 1.9 \times 10^{17} \text{ cm}^{-3}$) grown by MOCVD were used. Three types of surface treatment were applied to the surface of p-type GaN before metal deposition. The first set was as-grown p-type GaN. The second set was prepared by dipping the p-type GaN in HCl solution for 1 minute. The third set was immersed into boiling aqua regia for 10 minutes. 100 Å-thick Pt was deposited on transmission line method pattern formed on the treated surface, followed by lift-off. The contact resistivity drastically decreased from $4.7 \times 10^{-1} \text{ ohm-cm}^2$ (HCl-treated sample) to $4.8 \times 10^{-4} \text{ ohm-cm}^2$ by the aqua regia treatment. In the photoemission spectra, Ga3d and N1s core level peaks shift to a lower binding energy in sequence with the HCl and the aqua regia treatment, indicating the reduction of band bending at the surface of p-type GaN. The intensity of O1s photoelectrons was significantly reduced by the aqua regia treatment. This indicates that the aqua regia treatment has a strong effect on the removal of surface oxide formed on GaN during MOCVD growth. In the valence band spectra of the aqua-regia-treated sample, the Fermi level decreased by 1.2 eV, thereby approached to 0.3 eV above the valence band maximum. This clearly provides evidence that the Schottky barrier height at the Pt/GaN interface is reduced by the aqua regia treatment. In HCl-treated sample, removal of the oxide was not completed. The surface oxides act as an impeding layer for the transport of holes from Pt to p-type GaN, via the increase of barrier height at the surface, resulting in the higher contact resistivity. When the surface oxides were removed by the aqua regia treatment, a number of Ga vacancies VGa, acting as acceptor for electrons, was found at the subsurface of p-type GaN. This supports that acceptor-type defects dominantly exist at the subsurface of p-type GaN. Thus, the Fermi level shifts to an energy level of acceptor defects, as indicated in the valence band spectra. Consequently, the Schottky barrier height is reduced, resulting in the decrease of contact resistivity. Using these results, Fermi level pinning of Pt contact on p-type GaN will be discussed.

2:00 PM, J3

Roles of NiO Layer on Electrical Properties of NiAu-Based Ohmic Contacts for p-GaN: *Yasuo Koide*¹; T. Maeda¹; Masanori Murakami¹; ¹Kyoto University, Dept. of Matls. Sci. and Eng., Sakyo-ku, Kyoto 606-8501 Japan

One of concerns to use group III-Nitride semiconductors in the manufacturing devices is lack of low-resistance Ohmic contacts for p-GaN. Although various approaches have been made to develop such the low resistance Ohmic contact materials, no success has been reported. Recently, a new approach to reduce the specific contact resistances (ρ_c) was developed by annealing Au-based Ohmic contacts in a partial O_2 ambient, and the reduction of the ρ_c values by a factor of around 3 was obtained. However, the reason why the addition of O_2 to N_2 ambient reduced the ρ_c value was not understood. Two controversial mechanisms have been reported to explain the ρ_c reduction: (1) formation of an intermediate semiconductor layer (ISL) with high hole concentrations, caused by removal of hydrogen atoms which bonded with Mg or N atoms in the p-GaN epilayer, and (2) formation of a p-NiO layer directly on the p-GaN epilayer surface, resulting in reduction of the Schottky barrier height (ϕ_b) at the p-GaN/metal interface. The purpose of the present paper is to understand whether the NiO layer forms the ISL with high p-type doping concentration or low energy barrier between the metals and the p-GaN by measuring the electrical properties of Au-based Ohmic contacts with the NiO layers. (0001)-oriented Mg-doped p-GaN epilayers were grown by MOVPE on (11-20)-oriented $\alpha\text{-Al}_2\text{O}_3$ substrates using a thin AlN buffer layer. The hole concentration was $4\text{-}5 \times 10^{17} \text{ cm}^{-3}$. A variety of the NiAu-based contacts with the NiO layers such as NiO/Au, NiO(Li)/Au, Ni/NiO(Li)/Au, Ni/Li₂O/NiO/Au, and Ni/Li₂O/Ni/NiO/Au contacts were prepared. The NiO layers were prepared by the RF sputter-deposition technique. To obtain the p-type NiO layer, Li was added to the NiO layers by sputtering a Li₂O circular target place on the Ni target. After lifting off the photoresist, annealing was carried out in the O_2 ambient at tempera-

tures lower than 500°C. NiO layers doped with Li had a p-type conduction with resistivity of around 1 Ω-cm after annealing at temperatures lower than 500°C. However, all the NiO-based Ohmic contacts did not provide the ρ_c values lower than that ($\rho_c \equiv 10^{-2}$ Ω-cm²) of the conventional Ni/Au contacts prepared by annealing in N₂ ambient. From the present result, it was believed that the p-NiO layer did not act as the ISL to reduce the ϕ_B at the p-GaN/Au interface.

2:20 PM, J4 +

A New Methodology for Measuring Barrier Height and Ideality Factor of Metal Contacts to p-type GaN: Douglas L. Hibbard¹; Cynthia L. Jensen¹; Danny Feezell¹; YongSheng Zhao¹; Henry P. Lee¹; Z. J. Dong²; R. Shih²; ¹University of California-Irvine, Elect. and Comp. Eng. Dept., c/o Dr. Henry Lee, 2231 Engineering Gtwy., Irvine, CA 92697 USA; ²Alpha Photonics Incorporated, 2019 Saturn St., Monterey Park, CA 91754 USA

The performance of current GaN based light emitting devices is severely limited by the inherently high contact resistance of p-GaN. Many strategies incorporating different materials and processing technologies have been investigated to reduce this problem. Most researchers report contact performance in terms of specific contact resistance. However, this can lead to erroneous conclusions if the applied current density is not specified since the current transport characteristics of known p-GaN based systems are non-linear. More useful evaluation parameters are Schottky barrier height, ϕ_B , and diode ideality factor, n , which are more fundamentally descriptive of the metal to p-GaN system. Unfortunately, there is no universal agreement on the proper methodology for extracting ϕ_B from I-V measurements of that system. In general, I-V data is measured between a pair of contacts, a circular dot and a large surrounding pad and fitted by a thermionic transport model. However, the uniquely high resistivity of p-GaN limits the quantitative accuracy of that procedure. Specifically, previous work did not fully account for the voltage drop at the second, non-ohmic contact; the voltage lost within the p-layer itself; and the current crowding effect, constricting the active electrode areas. In this paper, we present a new technique for measuring ϕ_B on GaN LED epi-wafers that addresses these weaknesses. Principally, an ohmic contact to the p-GaN is formed independently of any processing of the metal dot contact of interest. We utilize three electrical probes spaced about 1 mm apart. Passing a high density current between probes 1 and 2, which are in direct contact with the wafer surface, damages the p-n junctions of the epilayer at localized spots yielding ohmic behavior. By subsequently probing between probe 3, which rests on the dot, and probe 2, the I-V characteristics of the dot can be studied in isolation. Two corrections to the data are then necessary. First, not all of the terminal voltage is dropped over the dot contact. Ignoring this effect causes an underestimate of the true ϕ_B value. We corrected for this voltage drop by using a modified Norde function in which the series resistance is extracted from the I-V data. Second, since current transport is restricted to the perimeter of the dot, an overestimate of the true ϕ_B value occurs if one does not account for this current crowding. Using the I-V data in conjunction with HSPICE simulation of a distributed diode/resistor circuit corresponding to the test structure, a more accurate contact area was calculated. Finally, we compare the results from our technique to those using methods previously reported for Ni/Au and other contact systems. We believe that this improved procedure represents the most accurate approach reported to date for determining ϕ_B for contacts on p-GaN and related materials. As such, it offers a more consistent platform from which technological progress can be evaluated.

2:40 PM, J5 +

Effect of Surface Treatment on the Change of Domain Size in Pd Contact on p-type GaN: Jong Kyu Kim¹; Tae Sik Cho¹; Jung Ho Je¹; In-Ok Jung²; Byung-Teak Lee²; Jae Won Lee³; Yong Jo Park³; Taeil Kim³; Jong-Lam Lee¹; ¹Pohang University of Science and Technology, Matls. Sci. and Eng. Dept., San 31 Hyoja-Dong, Pohang, Kyungbuk 790-784 South Korea; ²Chonnam National University, Dept. of Metall. Eng., Kwangju, Chonnam 500-757 South Korea; ³Samsung Advanced Institute of Technology (SAIT), Photo. Lab., Suwon, Kyunggi-Do 440-600 South Korea

The pre-surface treatments using boiling aqua regia and (NH₄)₂Sx before Pd deposition were effective to reduce contact resistivity as low as 10-5ohm-cm². However, no works were conducted on the annealing effect on both changes of contact resistivity and microstructure. In the

present work, we investigated dependence of microstructural change on the pre-surface treatment prior to Pd deposition using synchrotron x-ray scattering measurements. The results were used to interpret the role of microstructural change on the variation of contact resistivity. The p-type GaN films($\rho=1.9 \times 10^{17}$ cm⁻³) grown by MOCVD were used. The first set was immersed into boiling aqua regia for 10 minutes to remove surface oxides. The second set was prepared by immersing the aqua regia-treated sample into (NH₄)₂Sx for 10 minutes to protect the clean surface from the formation of native oxide during air exposure. 200Å-thick Pd was deposited on the treated surface, and annealed at the temperature of 300 and 500°C for 30 seconds under N₂. For the aqua regia-treated sample, the contact resistivity increased from 6.2X10⁻³ to 2.2X10⁻²ohm-cm² after annealing at 300°C, but decreased to 3.5X10⁻³ohm-cm² at 500°C. But, the contact resistivity slightly degraded from 8.4X10⁻⁴ ohm-cm² to 1.6X10⁻³ohm-cm² at 300°C and to 1.0X10⁻³ohm-cm² at 500°C for the (NH₄)₂Sx-treated sample. It was found that the crystal domain size depends on the type of surface treatment and increases with annealing temperature. In the aqua regia-treated sample, the crystal domain size in surface normal direction of Pd films increased from 205Å to 214Å at 300°C and 220Å at 500°C. In the (NH₄)₂Sx-treated sample, it increased from 114Å to 135Å at 300°C and 158Å at 500°C. Ga and N atoms could be outdiffused through domain boundaries, pipe diffusion, especially at low temperature. The outdiffusion of host atoms of GaN is controlled by the formation of molecules at the surface of Pd because host atoms occupying domain boundaries suppress next atoms to diffuse out. Free energy change for the reaction, N+N-N₂, is -849,9kJ/mol, but 357.5kJ/mol for the reaction of Ga+Ga-Ga₂. This suggests that the pipe diffusion of N atoms proceeded for the Pd contacts, but Ga atoms were suppressed. Thus, N vacancies, act as donor, were produced, thereby reduced the net concentration of holes. Therefore, contact resistivity rapidly increased with annealing temperature. Contact resistivity at 300°C was less degraded in (NH₄)₂Sx-treated GaN. This could be explained by a barrier effect of sulfur atoms with mono-layer at the Pd/p-type GaN interface. At 500°C, both Ga and N atoms could outdiffuse independent of the type of surface treatment, resulting in the decrease of contact resistivity in the aqua-regia-treated sample. These phenomena were confirmed using both TEM with high resolution and synchrotron x-ray photoemission spectroscopy.

3:00 PM Break

3:40 PM, J6 +

Characterization of AlGaN Surfaces after Various Kinds of Surface Treatments: Shinya Ootomo¹; Susumu Oyama¹; Tamotsu Hashizume¹; Hideki Hasegawa¹; ¹Hokkaido University, Rsch. Ctr. for Interface Quan. Elect. (RCIQE), Kita-ku North 13 West 8, Grad. Sch. of Elect. and Info. Eng., Sapporo, Hokkaido 060-8628 Japan

AlGaN/GaN high electron mobility transistors (HEMTs) are very promising for applications in high-voltage/high-power electronic devices operating at microwave/millimeter wave frequencies. In order to improve performances of the AlGaN/GaN HEMTs, it is indispensable to understand and control the properties of AlGaN surfaces for successful surface passivation and formation of Schottky and ohmic contacts. In this paper, we systematically investigate properties of AlGaN surfaces after various kinds of surface treatments by XPS, AES, AFM and Raman measurements. AlGaN/GaN heterostructure samples grown on (0001) sapphire substrates by metalorganic vapor phase epitaxy (MOVPE) were used in this study. The Al content of the AlGaN layers is 17-25%. From the viewpoint of actual device fabrication process, sample surfaces were cleaned in organic solvents and then an NH₄OH solution at 50°C for 15 min. A dry cleaning was performed by exposing the AlGaN surface to the ECR N₂ plasma and the ECR H₂ plasma at 300°C for 1-15 min in the ECR-CVD chamber. The two-dimensional electron gas (2DEG) concentration and mobility in the AlGaN/GaN heterostructure were 1 x 10¹³ cm⁻² and 1300 cm²/Vs at room temperature, respectively. The presence of a 2DEG at the heterointerface was clearly confirmed by Shubnikov-de Hass (SdH) oscillation at 2 K. In the Raman spectra from the AlGaN/GaN heterostructure sample, the E₂ (high) line was clearly detected at 570 cm⁻¹ and exhibited a narrow linewidth comparable to that of the reference GaN sample. These results indicated that our heterostructure sample has high quality of AlGaN layers and the AlGaN/GaN interface. A high intensity of the XPS O1s level was observed on the AlGaN surface treated in organic solvents. Based on the angle-resolved XPS analysis, the O1s and

Al2p components were found to rapidly increase and the Ga3d component slightly decreased, as the escape depth decreased. These mean that the AlGaIn surface treated only in organic solvents was covered with natural oxides and that the Al-oxide component is dominant on the topmost AlGaIn layer in spite of the fact that the Al content is below 25%. Such oxygen-related peaks almost disappeared in the XPS spectra after the NH₄OH treatment. The NH₄OH-treated surfaces gave a constant in-depth composition distribution with a near-stoichiometric composition. The Raman peak intensity from the AlGaIn lattice was enhanced after the NH₄OH treatment. Thus, these results strongly demonstrated that the NH₄OH treatment process is very effective in realizing oxide-free and well-ordered AlGaIn surface. The ECR N₂ and H₂ plasma treatments were also found to remove the natural oxide layer from the AlGaIn surface.

4:00 PM, J7 +

Ohmic Contacts and Schottky Barriers to n-AlGaIn: *Eric D. Readinger*¹; Joon Seop-Kwak¹; Brian P. Luther¹; Christopher J. Eiting²; Damien J. H. Lambert²; Russell D. Dupuis²; Suzanne Mohney¹; ¹Penn State University, Depts. Matls. Sci. and Eng., 207 Steidle Bldg., University Park, PA 16802 USA; ²The University of Texas at Austin, Microelect. Rsch. Ctr., PRC/MER-R9900, Austin, TX 78712-1100 USA

With growing interest in AlGaIn for UV detectors and electronic devices, the problem of forming high quality electrical contacts to this semiconductor has become increasingly important. Here we present results on both ohmic contacts and Schottky barriers to n-AlGaIn. The AlGaIn films were grown by MOCVD. For ohmic contacts, the effect of the Ti/Al ratio on the contact behavior was studied. Contacts were evaluated on 1.2 microns thick n-Al_{0.31}Ga_{0.69}In epilayers, having a bulk carrier concentration of 2.3×10^{18} cm⁻³. The Ti/Al ratio was controlled by the metal film thicknesses, and the atomic percent Al in the contact varied from 23-78%. Rapid thermal annealing of the contacts was performed in an Ar or N₂ ambient at 600-1050°C. Most contact compositions exhibited linear current-voltage characteristics when annealed at or above 850°C for 30 s. The compositions Ti (55nm)/Al (115nm) and Ti (75nm)/Al (115nm) were found to provide ohmic contacts following the mildest annealing conditions, with the best contact resistivities at 5×10^{-5} Ω-cm. Microscopy revealed that contacts containing a higher atomic percent Ti were much smoother after annealing. Little difference was found when comparing Ti/Al contacts annealed in Ar versus an N₂ ambient; however, multi-layers of Ti/Al/Ti/Au showed that varying the layer composition and annealing environment may contribute to the lowest obtainable specific contact resistance. Schottky contacts were fabricated on n-Al_{0.14}Ga_{0.86}In by thermal evaporation of Au. The epilayer was 1.7 microns thick, having a bulk carrier concentration of 5×10^{17} cm⁻³. Different surface preparations were investigated, including a standard solvent clean (acetone, methanol and DI rinse), boiling aqua regia, HCl: DI (1:1), and KOH solution. As a control, some samples did not receive a surface preparation (no etch) before metal deposition. I-V and C-V characteristics of these Schottky contacts showed remarkable change with exposure to air at room temperature over a period of only days. These diodes showed an increase in barrier height on the order of 0.3-0.5 eV, a decrease in ideality factors from greater than 2 to ~1.3, and a decrease in reverse currents at 5 Volts by ~6 orders of magnitude. Similar samples that were kept under vacuum for the same time frame showed no improvement in Schottky contact characteristics and remained very non-ideal, demonstrating the strong influence of the ambient on unpassivated AlGaIn devices.

4:20 PM, J8 +

NiAl as a Thermally Stable Ohmic Contact to n-GaN: *Christopher M. Peltó*¹; Douglas B. Ingerly¹; Y. Austin Chang¹; Yong Chen²; R. Stanley Williams²; ¹University of Wisconsin-Madison, Matls. Sci. Pgm., 1509 University Ave., Madison, WI 53706 USA; ²Hewlett-Packard Laboratories, 3500 Deer Creek Rd., 26U, Palo Alto, CA 94304 USA

We have investigated the use of the intermetallic compound NiAl as an ohmic contact to n-GaN in an attempt to develop a more thermally stable contact. Despite the success of the ohmic contacts currently employed in commercial light emitting and laser diodes, the search for low resistance contacts is not over. The application of the III-nitrides to high-power, high-temperature devices is likely to require new contacts due to the need for superior thermal stability. Based upon the results of a combined thermodynamic and kinetic model, the reaction between the

NiAl and the GaN should create a desirable interface for current transport based on the commonly held theories for ohmic contact formation to n-GaN. Additionally, the refractory nature of the NiAl metal suggests that it will perform well at elevated temperatures. By selecting a metallization that can provide a controlled reaction interface we are also trying to acquire a firmer understanding of the poorly understood mechanism responsible for the low resistance contacts to n-GaN. The electrical behavior of the NiAl/n-GaN contacts was characterized after both rapid thermal annealing and long-term annealing treatments. The electrical measurements demonstrated NiAl to be an excellent ohmic contact with a specific contact resistance comparable to that of Ti/Al characterized on the same n-GaN substrate. Long-term anneals at elevated temperature showed that the contact remained ohmic, with only a slight increase in the specific contact resistance. In addition to the electrical measurements, the NiAl/n-GaN contacts were characterized metallurgically by Auger depth profiling, SEM, and x-ray diffraction studies to investigate the effects of the different annealing processes on the contact structure's chemistry and integrity. We also intended to confirm that the contact behaves according to the thermodynamic/kinetic model predictions.

4:40 PM, J9 +

Novel Contact System for II-VI Laser Diodes: *Oliver Schulz*¹; Matthias Strassburg¹; Udo W. Pohl¹; Dieter Bimberg¹; S. Itoh²; K. Nakano²; A. Ishibashi²; M. Klude³; D. Hommel³; ¹Technical University Berlin, Institut für Solid State Phys., Sekr. PN 5-2, Hardenbergstrasse 36, Berlin 10623 Germany; ²Sony Corporation, Shinagawa-ku, Tokyo 141-0001 Japan; ³University Bremen, Institut für Solid State Phys., Kufsteiner Strasse NW1, Bremen 28359 Germany

Pd/Au based electrodes on a ZnTe/ZnSe MQW contact layer are representing the standard p-type contact system for II-VI optoelectronic devices. Electrode lifetimes for cw operating II-VI lasers of 1000h are reported, but a further improvement is indispensable for commercial applications. An increase of the electrode lifetime can be achieved by a reduction of the contact resistance and furthermore by a decrease of the series resistance. The specific contact resistance mostly depends on the barrier height and the doping level. The barrier height is determined by the metal-semiconductor system, but the doping level presents a tool to lower the specific contact resistance and therefore for the serial resistance. Decreased heat generation because of the lower resistivity is the key for an increase of the electrode and device lifetimes. In order to achieve a low resistivity metal-semiconductor contact we investigated the influence of a thin lithium nitride layer between the semiconductor contact layer and the metallisation. Lithium nitride is known as an acceptor source for MOCVD grown ZnSe, but using this technology no laser structures could be fabricated until now. The high process temperature for sufficient doping leads to an enhanced diffusion of Cd out of the active layer and finally to a degradation of the structure. Upon deposition of lithium nitride prior to metallisation we are able to create an additional doping in the contact area with an having an essential influence on the whole laser characteristics. Because of the high melting point of Palladium and Gold the metallisation after the lithium nitride deposition is leading to an indiffusion of additional dopants. Using this novel contactation technology we achieved threshold current densities of 30A/cm² and 42A/cm² for different laser structures with a simultaneous reduction of the threshold voltage by at least 1V. These threshold current densities are the lowest ever reported for any semiconductor laser. Lifetime extensions from 13min to 9h35min for the first structure and from 1min41sec to 40min14sec for the second one were observed. To investigate the lithium and nitrogen depth profile elastic recoil detection analysis (ERDA) and secondary ion mass spectrometry (SIMS) were used. The ERDA depth profile shows an indiffusion of 120nm of lithium as an order of magnitude of 10^{20} atoms/cm³, so that traces of lithium should go down to the p-cladding layers. A decrease of threshold current density and voltage with increasing acceptor concentration in the p-cladding layer was theoretically predicted by Nakatsuka et al.

5:00 PM, J10 +

Development of Highly Reliable PdZn-Based Ohmic Contacts for p-type InP: *Hirokuni Asamizu*¹; Akira Yamaguchi²; Shinya Konishi¹; Yasuhiro Iguchi²; Tadashi Saitoh²; *Yasuo Koide*¹; *Masanori Murakami*¹; ¹Kyoto University, Dept. of Matls. Sci. and Eng., Yoshidahon-machi, Sakyo-ku, Kyoto 606-8501 Japan; ²Sumitomo Electric Industries Limited, Opto-elect. Rsch. Lab., 1-1-3, Shimaya, konohana-ku, Osaka 554-0024 Japan

The conventional approach to fabricate Ohmic contacts for p-InP involves the use of Au-based metallizations, such as AuZn and AuBe. Although these Au-based contacts yield satisfactory low contact resistance, they have deep protrusion of Au into the InP and poor thermal stability after contact formation. These properties cause poor fabrication yield and poor reliability during device operation. In addition, the optimum annealing temperature to produce low resistance Au-based Ohmic contacts for p-InP is about 100°C higher than that of AuGeNi Ohmic contacts used extensively for n-type contacts (350-400°C). If the annealing temperature for p-type Ohmic contacts is reduced to 350-400°C, simultaneous preparation for p- and n-InP Ohmic contacts will be achieved by one step annealing, leading to significant reduction of device production costs of the InGaAs/InP p-i-n photodiodes. The purpose of the present study is to develop highly reliable Au-free Ohmic contacts for p-InP, which provide low contact resistance by annealing at temperatures in the range of 350 to 400°C. The wafers used in this study were S-doped InP(100) substrates covered by undoped InP epitaxial layers with 5µm thickness. The p-type channels were fabricated by diffusing Zn into the undoped InP surface layers through the SiN_x mask. The carrier concentration of the InP surface was about 4x10¹⁸cm⁻³. Prior to contact metallization deposition, the surface of the p-InP layer was chemically cleaned. Then, Sb, Zn, and Pd layers were deposited sequentially in an electron-beam evaporator. Patterning of the metal films was performed using the conventional lift-off technique for the electrical property measurements. These specimens were then annealed in the conventional furnace in forming gas (5% H₂:95% N₂). The contact resistivity was determined using the transmission line method. Cross-sectional transmission electron microscopy was primarily used for structural analysis. The minimum specific contact resistivity of 7x10⁻⁵Ωcm² was obtained for the Sb (3nm)/Zn (20nm)/Pd (20nm) contact after annealing at temperature ranging from 375°C to 400°C for 2 min, where a slash (/) sign indicates the deposition sequence. This contact had excellent reproducibility and smooth surface morphology. In addition, the diffusion depth of the contact metals into InP substrate was very shallow of less than 50nm. The specific contact resistivity of the Sb/Zn/Pd contact did not deteriorate even after annealing at 300°C for 2h, indicating that the contact had excellent thermal stability. Use of this PdZnSb contact materials for p-InP will make it possible to fabricate simultaneously p- and n-type Ohmic contacts by annealing at the same temperatures, leading to significant reduction of the device fabrication cost. The roles of each element added to the contact materials on the electrical properties will be discussed at the conference.

Session K. Si-Based Heterostructures

Wednesday PM Room: Main: 186, Satellites: 253-254
 June 21, 2000 Location: Sturm Hall

Session Chairs: Ya-Hong Xie, University of California-Los Angeles, Matl. Sci. and Eng. Depts., Los Angeles, CA 90095-1595 USA; Bruce Wessels, Northwestern University, Evanston, IL 60208 USA

1:20 PM, K1 +
Carrier Mobilities and Process Stability of n- and p- Surface Channel Strained Si/SiGe MOSFETs: *Matthew T. Currie*¹; Christopher W. Leitz¹; Eugene A. Fitzgerald¹; Mark A. Armstrong²; Dimitri A. Antoniadis²; ¹Massachusetts Institute of Technology, Depts. of Matls. Sci. and Eng., 77 Massachusetts Ave., Rm. 13-5142, Cambridge, MA 02139 USA; ²Massachusetts Institute of Technology, Depts. of Elect. Eng. and Comp. Sci., 77 Massachusetts Ave., Rm. 39-415B, Cambridge, MA 02139 USA

Relaxed graded SiGe buffer technology provides a high-performance and economical method to extend the speed and functionality of the traditional Si platform. For example, the utilization of strain and bandgap engineering in the Si/SiGe system enables the manufacture of high-speed

transistors for next-generation microelectronics. Tensile strained Si on relaxed SiGe exhibits enhanced carrier mobilities via reduction in both effective mass and intervalley scattering, translating directly into increased device performance. Additionally, strained Si transistors have been shown to exhibit increased electron velocity overshoot, providing an additional performance boost at short channel lengths. A surface strained Si channel provides the additional benefits of a high-quality Si-SiO₂ interface for MOS structures, the feasibility of strained Si PMOS devices, and carrier mobility enhancement even at high vertical fields. We have fabricated long-channel surface strained Si n- and p-MOSFETs on relaxed graded SiGe substrates (10-30% Ge content) to study the effects of strain on effective carrier mobilities. To facilitate a high-throughput study of this nature, we have fabricated the devices using a short-flow, one mask level process with a deposited SiO₂ gate dielectric and 1000°C source/drain implant anneals. Our NMOS devices exhibit peak effective mobilities of over 1000 cm²/Vs and electron mobility enhancements of up to 1.8 over coprocessed bulk Si devices in vertical fields up to 8x10⁵ V/cm. Likewise, our PMOS devices have peak effective hole mobilities of over 200 cm²/Vs and mobility enhancements of up to 1.4 at vertical fields up to 6x10⁵ V/cm. These results are comparable to or better than all results on similar devices published to date. Because the rough surface crosshatch of relaxed SiGe substrates is problematic for fine-line lithography, we have also fabricated identical devices with an intermediate planarization step. The devices fabricated on these substrates display similar results, demonstrating that the surface crosshatch pattern can be eliminated without degrading device performance. We have also processed devices with boron and phosphorous well implants to determine the effect of such an implant on carrier mobility. While the low-field mobilities in these samples are degraded due to increased ionized impurity scattering, both the high-field mobilities and overall mobility enhancements are maintained, demonstrating the process stability of these device structures.

1:40 PM, K2 +
Post-Growth Annealing Effect on Electrical and Structural Properties of High Ge Content Si_{1-x}Ge_x/Si_{1-y}Ge_y/Si(001) P-Type Modulation Doped Heterostructures: *Maksym Myronov*¹; Carl P. Parry¹; Evan H.C. Parker¹; Terry E. Whall¹; Janet M. Bonar²; ¹University of Warwick, Dept. of Phys., Coventry CV4 7AL UK; ²University of Southampton, Depts. of Elect. and Comp. Sci., Southampton SO17 1BJ UK

The growth of high-quality Si_{1-x}Ge_x epilayers with x>0.5 on Si substrates by molecular beam epitaxy (MBE) is of great interest both for device applications and fundamental research. The main problem in growing Si_{1-x}Ge_x alloy on a Si substrate is the lattice mismatch, which increases from 0 to 4.2% as x is varied from 0 to 1. The larger x becomes, the thinner the Si_{1-x}Ge_x channel has to be grown in order to prevent misfit dislocations from relaxing the strain. One of the possibilities to obtain Ge concentrations x>0.5, while retaining strain in the Si_{1-x}Ge_x layer, is to use relaxed Si_{1-y}Ge_y substrates with the bulk lattice constant of the Si_{1-y}Ge_y. This allows either strained Si, Ge or Si_{1-x}Ge_x to be grown on an underlying Si wafer. Such substrates are termed virtual substrates (VS). The transport and structural properties of Si_{1-x}Ge_x/Si_{1-y}Ge_y/Si(001) p-type modulation doped heterostructures with Ge composition in the channel x=0.8, 0.78, 0.76, 0.6 and in the VS y=0.35, 0.3 grown by a combination of solid source MBE and Low Pressure CVD on Si(001) are reported. The heterostructures were grown at relatively low temperatures to avoid strain induced roughening of the channel. To improve the electrical characteristics of grown structures annealing treatments were performed following growth in nitrogen atmosphere in the temperature range of 600-900°C for 30min. Cross-sectional TEM was performed on these heterostructures to determine the structural integrity of the epilayers and also to determine the dislocation microstructure of relaxed virtual substrate. In all annealed samples, we observed broadening of the Si_{1-x}Ge_x channel. The mobility and sheet carrier density were measured by the Hall technique (van der Pauw cross geometry) in the temperature range of 9-300K. For all samples annealing at 600°C is seen to have a negligible effect on the mobility. Increasing the annealing temperature results in pronounced successive increases in mobility. Each structure has an optimum annealing temperature, which depends on heterostructure design and growth conditions. A moderate decrease in the sheet carrier density with annealing is observed. This decrease was found to be consistent with the decreased hole transfer from the doping region to the channel due to Ge and

Si interdiffusion in the buffer/channel/spacer region during thermal annealing, resulting in decreased Ge concentration in the channel and as a consequence the valence-band offset is decreased. This was confirmed by numerical solution of Shrodinger-Poisson simulation for studied heterostructures. The best mobility in this research was obtained after annealing treatments for $\text{Si}_{0.2}\text{Ge}_{0.8}/\text{Si}_{0.65}\text{Ge}_{0.35}/\text{Si}(001)$ heterostructure. At 9K we observed an increase in mobility (at sheet carrier density) from $655\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ ($1.43 \times 10^{12}\text{cm}^{-2}$), in an as-grown sample, up to $1930\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ ($8.8 \times 10^{11}\text{cm}^{-2}$) in annealed at 700°C one.

2:00 PM, K3 +

High Quality Thermal Ultra-Thin Gate Oxide Directly Grown on High Temperature Formed $\text{Si}_{0.3}\text{Ge}_{0.7}$: S. B. Chen¹; C. H. Huang¹; Y. H. Wu¹; W. J. Chen¹; Albert Chin¹; ¹National Huwei Institute of Technology, Dept. of Mech. Matls. Eng., Huwei, Taiwan

Although SiGe p-MOSFETs have demonstrated excellent device performance, the major obstacle to apply SiGe p-MOSFETs into current CMOS technology is the required low temperature processing ($<800^\circ\text{C}$) to avoid strain relaxation generated defects and much degraded device performance. Unfortunately, the low temperature processing is unable to comparable with the necessary high temperature rapid thermal annealing used for implantation activation. Furthermore, gate oxide integrity is also much degraded using low temperature oxides. Recently, we have reported that high current drive capability can be obtained in strain relaxed $\text{Si}_{0.3}\text{Ge}_{0.7}$ p-MOSFETs and 2 times higher mobility than Si devices is achieved. The high drain current and mobility is due to high Ge content even without the strain, but the improved device performance is expected to increase the operation speed of existing CMOS and reduce the circuit area up to 33%. In this study, we have further investigated the gate oxide integrity of ultra-thin thermal oxides direct grown on high temperature formed $\text{Si}_{0.3}\text{Ge}_{0.7}$. The 3nm and 5nm thermal oxides used for 0.18 and 0.25 μm technology were grown at $900\text{-}950^\circ\text{C}$ and gate oxide integrity was examined by leakage current, breakdown field, interface-trap density, stress-induced leakage current, and charge-to-breakdown. The gate oxide leakage current and breakdown field improve as decreasing oxide thickness from 5nm to 3nm and becomes comparable with control thermal oxide grown on Si. Low interface-trap density of 5.9×10^{10} and 4.0×10^{10} $\text{eV}^{-1}\text{cm}^{-2}$ are obtained for 5nm and 3nm oxides grown on $\text{Si}_{0.3}\text{Ge}_{0.7}$ with low oxide charge density of $\sim -5\text{-}6 \times 10^{10}$ cm^{-2} for both thickness. The low interface and oxide charges are due to the extremely smooth oxide/ $\text{Si}_{0.3}\text{Ge}_{0.7}$ interface as observed by cross-sectional TEM and AFM. We have also studied the reliability of oxides grown on $\text{Si}_{0.3}\text{Ge}_{0.7}$. Small stress-induced leakage current less than 50% is measured after -3.3V stress for 10,000s. Good SiGe oxide reliability can be evidenced by the high QBD of 0.11 C/cm^2 that is comparable with published thermal SiO_2 data under a -4.5V constant voltage stress. The good gate oxide integrity is due to the high temperature formed and strain-relaxed $\text{Si}_{0.3}\text{Ge}_{0.7}$ that has a original smooth surface and stable after subsequent high temperature process.

2:20 PM, K4 +

Germanium Photodetectors Integrated on Silicon for Si Microphotonics: Hsin-Chiao Luan¹; Desmond R. Lim¹; Douglas D. Cannon¹; Lionel C. Kimerling¹; Lorenzo Colace²; Gianlorenzo Masini²; Gaetano Assanto²; ¹Massachusetts Institute of Technology, Depts. of Matls. Sci. and Eng., 13-4130, 77 Massachusetts Ave., Cambridge, MA 02139 USA; ²Terza University of Rome, Dept. of Elect. Eng. and Natl. Instit. for Phys. of Mat., Via della Navale 84, Rome 00146 Italy

We have fabricated heterojunction Ge/Si photodetectors that exhibit responsivity of 550 mA/W at 1.32 μm , 250 mA/W at 1.55 μm and response times shorter than 850 ps. These photodetectors were fabricated using an uncomplicated Si compatible process that can be integrated as part of the front-end process in Si CMOS processing technology. High quality Ge epilayers in these photodetectors were grown on Si by a two-step ultrahigh vacuum/chemical-vapor-deposition (UHV/CVD) process. Two-step UHV/CVD allows the epitaxial growth of Ge on Si without islanding. Threading-dislocations (TD) in Ge epilayers were reduced by cyclic thermal annealing. On large Si wafers, a reduction of TD density from $1\text{e}9$ cm^{-2} to $2.2\text{e}7$ cm^{-2} was obtained. Combining selective-area-growth with cyclic-thermal-annealing produced an average threading-dislocation density of $2.3\text{e}6$ cm^{-2} . We also demonstrated small 10 μm \times 10 μm mesas of Ge on Si with no threading-dislocations. Cross-sectional transmission-electron-microscopic (XTEM) studies of these Ge

epilayers showed that sessile TDs can be reduced by annealing. This is contradictory to previous understanding. A mechanism will be proposed to explain this observation. Mesa photodetectors and metal-semiconductor-metal photodetectors were fabricated by standard lithography and wet chemical etching. Photo-response was measured by standard lock-in technique. We measured a charge carrier collection efficiency of 95%, an electron mobility of 3500 cm^2/V and a carrier lifetime of 0.8 ns. These measurements show that efficient high speed Ge photodetectors can be made using our material. Our processing technology and materials are suitable for the integration of Ge photodetectors with Si CMOS technology. Applications for our technology include Si Microphotonic applications such as detectors for fiber-to-the-home receiver and optical interconnects.

2:40 PM, K5 +

Growth of High Mobility $\beta\text{-FeSi}_2$ Continuous Films of its Conduction Type by Si/Fe Ratios: Ken-ichiro Takakura¹; Takashi Suemasu¹; Yoshihiro Ikura¹; Fumio Hasegawa¹; ¹University of Tsukuba, Instit. of Appl. Phys., 1-1-1 Tennohdai, Tsukuba, Ibaraki 305-8573 Japan

$\beta\text{-FeSi}_2$ is a promising material for Si-based optoelectronic devices, because it can be grown epitaxially on Si substrates and has a direct band gap of 0.83-0.87eV. Even non-doped $\beta\text{-FeSi}_2$, however, shows p- or n-type conduction with a very large carrier density of over 10^{18}cm^{-3} at room temperature (RT), and furthermore, its origin is not made clear yet. Most of $\beta\text{-FeSi}_2$ films were fabricated by ion beam synthesis (IBS) and were polycrystalline. The maximum electron and hole mobilities of these IBS films were usually a few hundred $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$. We have realized continuous and highly [100]-oriented $\beta\text{-FeSi}_2$ films from Si/Fe multilayers on Si (001) by high temperature annealing with a SiO_2 capping layer and templates. In this work, we found that the conduction type of these $\beta\text{-FeSi}_2$ films can be controlled by the Si/Fe ratio of the multilayers. The n- and p-type $\beta\text{-FeSi}_2$ films showed the maximum electron and hole mobilities of about 15 and 30 times higher than the highest values reported so far, respectively. The films were grown as follows: First, a 20 nm-thick [100]-oriented $\beta\text{-FeSi}_2$ template was grown epitaxially on high resistive a floating zone Si (001) substrate by reactive deposition epitaxy at 470°C . Next, nanometer-thick Si/Fe multilayers were deposited at RT. We deposited the Si/Fe multilayers corresponding to a 90 nm-thick $\beta\text{-FeSi}_2$ film including the templates. Finally, a $0.1\mu\text{m}$ -thick SiO_2 capping layer was deposited at RT and 900°C annealing was performed in Ar for 14h to grow [100]-oriented $\beta\text{-FeSi}_2$ films. The capping layer was introduced to prevent aggregation of the $\beta\text{-FeSi}_2$ films during the annealing. We prepared several samples with different Si/Fe ratios varying from 1.6 to 2.0. Hall measurements revealed that the $\beta\text{-FeSi}_2$ films with Si/Fe ratios of 1.9 and 2.0 showed n-type conduction, whereas those of 1.6, 1.7 and 1.8 showed p-type conduction. These results indicate that the conduction type of $\beta\text{-FeSi}_2$ can be controlled by a Si/Fe ratio. The carrier density at RT is, however, about 10^{18}cm^{-3} in all the samples, and origin of carrier is not made clear yet. The electron mobility of the sample with Si/Fe=1.9 was $500\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ at RT, and reached the maximum value of $6900\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ at 46K. The $\beta\text{-FeSi}_2$ film with Si/Fe=1.6 showed the hole mobility of $460\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ at RT, and a maximum value of $15000\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ at 50K. These maximum values are about 15 and 30 times larger than the highest values ever reported for the n- and p-type $\beta\text{-FeSi}_2$, respectively. Such high mobilities were attributed to a low scattering rate because of a large grain size of over $1.0\mu\text{m}$ as well as high [100] orientation of the grown films.

3:00 PM Break

3:40 PM, K6 *Invited

New Gate Dielectrics of Gd_2O_3 and Y_2O_3 Films for Si: J. Kwo¹; M. Hong¹; A. R. Kortan¹; K. L. Queeney¹; Y. J. Chabal¹; T. S. Lay²; J. P. Mannaerts¹; T. Boone¹; J. J. Krajewski¹; A. M. Sergent¹; J. M. Rosamilia¹; ¹Lucent Technologies, Bell Labs., 600 Mountain Ave., Murray Hill, NJ 07974 USA; ²National Sun Yat-Sen University, Instit. of Electro-Opt. Eng., Kaohsiung, Taiwan

The continuous miniaturization of Si electronics has imposed severe constraints on performances of the SiO_2 gate oxide, and calls for replacing dielectrics with a dielectric constant, ϵ , substantially greater than SiO_2 . One of the major requirements for the new dielectric materials is that they remain thermodynamically stable in contact with Si at temperature exceeding 1000K. The rare earth oxides are suitable candidates for several semiconductor substrates based on thermodynamic energy

considerations. In this work, single crystal and amorphous dielectric films of Gd_2O_3 ($\epsilon=12$) and Y_2O_3 ($\epsilon=18$) were prepared as gate dielectrics for Si by ultrahigh vacuum vapor deposition. Infrared absorption spectroscopy reveals that the interface between Gd_2O_3 and Si is free of SiO_2 segregation ($< 0.01\text{nm SiO}_2$). Absence of SiO_2 at the dielectric/Si interface is especially important because a significant thickness budget for the dielectric layer is gained, and this is one distinct advantage over other approaches using gate dielectric stacks. Since the control of the interfacial structure and chemistry is known to be critical, we show that the use of vicinal Si (100) substrates is the key to epitaxial growth of (110) oriented, single-domain films in the Mn_2O_3 structure. In conjunction with post forming gas anneals the single domain films showed a dramatic improvement in leakage current density from 10^{-1}A/cm^2 to 10^{-5}A/cm^2 at 1V for an epitaxial Gd_2O_3 film at an equivalent SiO_2 thickness of 1.9 nm. Furthermore, the amorphous rare earth oxide films form thin, smooth overlayers on regular Si surface. In particular, amorphous Y_2O_3 films 4.5 nm thick showed a leakage current as low as 10^{-6}A/cm^2 at 1V, and a specific capacitance as high as 35 fF/mm^2 at an equivalent SiO_2 thickness of 1.0 nm. This electrical leakage result is five orders of magnitude better than the state-of-art result of SiO_2 gate oxide 1.5 nm thick. The C-V curves of both epitaxial and amorphous films showed the transition from accumulation to depletion, inversion of carriers, and little hysteresis in reverse sweeping. Preliminary post annealing tests showed that the amorphous Y_2O_3 films remained stable with little degradation of dielectric properties after a brief anneal to 950°C . Hence the present investigation of the rare earth oxide Gd_2O_3 and Y_2O_3 dielectric films has demonstrated excellent characteristics satisfying major requirements for Si gate dielectric applications.

4:20 PM, K7 +

Epitaxial MgO Deposited on Si by Metal-Organic Molecular Beam Epitaxy using a Cubic-SiC Interlayer: *Brent H. Hoerman*¹; Feng Niu¹; Bruce W. Wessels¹; ¹Northwestern University, Mats. Sci. and Eng. Depts., 2225 N. Campus Dr., MLSB, Evanston, IL 60208 USA

The successful integration of ferroelectric oxides as thin epitaxial films on silicon would expedite the development of next-generation microelectronic, microwave, and integrated optical devices. The availability of a highly uniform, epitaxial layer of MgO on a Si substrate would facilitate such integration. We have successfully deposited epitaxial (100)MgO films on (100)Si using an interlayer of epitaxial cubic silicon carbide ($\beta\text{-SiC}$). Both of the films were grown by metal-organic molecular beam epitaxy (MOMBE) at 900°C . SiC forms a suitable template for MgO as the lattice mismatch (4%) is lower than that of MgO/Si (8 to 22%). SiC also resists oxidation at the MgO growth temperature and grows readily on Si. SiC layers 20 to 30 nm thick were grown. RHEED analysis and high resolution and conventional transmission electron microscopy (TEM) have confirmed the cube-on-cube nature of both epitaxial layers. High resolution TEM indicates an atomically abrupt SiC/Si interface. The MgO/SiC is also atomically abrupt with no evidence of SiO_2 formation. However, a high density of twins and stacking faults are observed in the SiC layer. This indicates the SiC layer accommodates the majority of the epitaxial mismatch strain. We have investigated the growth dynamics of the SiC interlayer which suggest epitaxy is achieved only below a critical flux of the carbon containing precursor. The influence of interlayer thickness on MgO epitaxy is also examined.

4:40 PM, K8

Negative Differential Resistance with Peak to Valley Ratio Greater Than 100,000 of Double Barrier $\text{CdF}_2/\text{CaF}_2$ Resonant Tunneling Diode on Si(111): *Masahiro Watanabe*¹; Toshiyuki Funayama¹; Taishi Teraji¹; Naoto Sakamaki¹; ¹Tokyo Institute of Technology, Rsch. Ctr. for Quant. Effect Elect., 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552 Japan

$\text{CdF}_2/\text{CaF}_2$ 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 ($\Delta E_c=2.9\text{eV}$) at the heterointerface. Due to the large ΔE_c and wide band gap energy of CdF_2 ($E_g=8\text{eV}$) and CaF_2 ($E_g=12\text{eV}$), resonant tunneling diodes (RTD) using $\text{CdF}_2/\text{CaF}_2$ 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_2 and CaF_2 have fluorite lattice structure and well lattice matched to Si with mismatches of -0.8%, +0.6% at room

temperature, respectively. Recently, epitaxial growth of $\text{CdF}_2/\text{CaF}_2$ heterostructures on Si(111) substrate using molecular beam epitaxy (MBE) and partially ionized beam epitaxy (PIBE) have been reported, and room temperature NDR characteristics with peak to valley ratio of 2-6 for $\text{CdF}_2/\text{CaF}_2$ RTD structures have been reported. In this paper, room temperature NDR characteristics with peak to valley ratio greater than 10^5 for $\text{CdF}_2/\text{CaF}_2$ double barrier resonant tunneling diode (DBRTD) have been reported for the first time. N-type Si(111) substrate with 0.1° misorientation was chemically cleaned and protective oxide layer was removed in ultra high vacuum chamber by thermal heating with Si flux. First of all, 1nm-thick CaF_2 was grown at 650°C , with ionization by electron bombardment without acceleration bias voltage (V_a). Ionization of CaF_2 was effective for improvement of CaF_2 flatness and coverage over Si surface because ionized CaF_2 or CaF tends to make strong bonding with Si. Subsequently, 3.7nm-thick CdF_2 quantum well layer was grown on the CaF_2 at 50°C . After the growth, the top CaF_2 barrier layer in 1nm in thickness was grown at 50°C with ionization and acceleration $V_a=500\text{V}$. Au/Al electrode of $18\mu\text{m}$ in diameter was fabricated by electron beam lithography and reactive ion etching (RIE). The RTD structure was designed so that electrons are injected from n-Si(111) substrate and tunneling through a 3.7nm-thick CdF_2 quantum well sandwiched by CaF_2 energy barriers to a Au/Al electrode. In the measurement of current-voltage characteristics, clear NDR characteristics with PVR more than 2 were observed at room temperature for 59% of the devices fabricated on the same wafer and PVR greater than 100000 has been observed for 3% on the same tip. Typical peak current was 0.1mA and bias voltage for peak current was around 1V. The NDR characteristic agreed well with theoretical estimation considering parasitic resistance. PVR nearly 10^6 is predicted theoretically using esaki-tsu formula without considering scattering of electrons. Dispersion of bias voltage giving the peak current was 0.6V, which almost corresponds to the layer thickness fluctuation of plus-minus one molecular layer of the CdF_2 quantum well layer. Influence of barrier thickness fluctuation will be also discussed.

5:00 PM, K9

Abrupt Oxide/Si Interface Formation Using As-Terminated Si for Ferroelectric Memory Device: *T. Chikyow*¹; M. Takakura²; M. Yoshimoto²; H. Koinuma²; ¹National Institute for Research in Inorganic Materials, Namiki 1-1, Tsukuba, Ibaraki 305-0044 Japan; ²Japan National Research Institute for Metals, Sengen 1-2-1, Tsukuba, Ibaraki 305-0047 Japan

An abrupt oxide/Si interface formation was demonstrated for the first time with a newly proposed As-termination method to Si surface. Recently functional oxide film growth on Si becomes an important technology and a typical case is a ferroelectric oxide materials on Si, which is applicable for the promising ferroelectric memory device. However, at the oxide/Si interface, thin SiO_2 layer or some amorphous layer are observed due to oxidation of Si surface and reaction between oxide and Si. To avoid the interfacial layers, a metal pre-deposition method was proposed by McKee. However, the method requires a sophisticated growth parameter control and it is not easy to apply to the practical LSI process. A key point of forming abrupt oxide/Si interface is to avoid SiO_2 formation during oxide material growth in oxygen atmosphere. A crucial point to realize abrupt interface is to terminate Si surface with an element which gives an inert surface to avoid oxygen absorption. Also the terminating elements must not make strained bonds to avoid oxidation at relatively low temperature. An As-terminated Si (001) surface is known as a surface with low free energy surface with less strain. As an example, CeO_2 was tried to grow at 500°C by Pulsed Laser Deposition on the As-terminated Si (001). A cross-sectional transmission electron microscope observation shows an abrupt CeO_2/Si interface. This method is basically applicable to another oxide film growth on Si. From the obtained result, As-termination in oxide film growth was found to be potentially useful for abrupt oxide/Si interface formation to realize ferroelectric memory devices.

Session L. Organic TFT's and Electronic Transport

Wednesday PM Room: Centennial Halls
June 21, 2000 Cafeteria

Session Chairs: J. Hendrik Schon, Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974-0636 USA; Jim Sturm, Princeton University, Ctr. for Photo. and Opto. Elec. Matls., Princeton, NJ 08540 USA

1:20 PM, L1 *Invited

Pentacene Organic Thin Film Transistors: *Tom Jackson*¹; ¹Penn State University, Elect. Eng. Dept., Ctr. for Thin Film Devices and Elect. Matls. and Process. Lab., University Park, PA 16802 USA

The performance of organic thin film transistors (OTFTs) has improved dramatically over the last several years and best performance is now comparable to, or better than, that of hydrogenated amorphous silicon-based (a-Si:H) devices. Thus far, small-molecule materials such as oligothiophenes and oligoacenes have shown the best performance. A number of these materials have a strong tendency to form molecular crystals and, when deposited by thermal evaporation onto substrates held at elevated temperature, they often form thin films with strong molecular ordering; such ordering may be important for obtaining large field-effect mobility and other desirable electrical characteristics. In particular, pentacene thin films deposited at a few angstroms/s onto substrates held at 50-100°C typically have micron-sized grains, and OTFTs using pentacene as the active layer have demonstrated field-effect mobility 2 cm²/V-s, current on/off ratio 10⁸, near zero threshold voltage, and sub-threshold slope 0.5 V/decade all these characteristics are similar to, or better than, those typically observed for a-Si:H thin film transistors (TFTs). More recently we have also demonstrated pentacene OTFTs with mobility 1 cm²/V-s on polymeric substrates. Organic thin film transistors can be used to fabricate circuits with sufficient speed for many applications. Using pentacene-based OTFTs and integrated level shifting to correct for normally-on devices we have fabricated simple circuits with delay less than 75 sec/stage. For these circuits the delay is dominated by level-shifting and directly driven inverters have sub-sec rise and fall times. We have also integrated OTFTs with a-Si:H TFTs to provide a simple complementary circuit technology. The field-effect mobilities of p-channel pentacene OTFTs and n-channel a-Si:H TFTs are similar, and integrated inorganic/organic TFT circuits can provide improved performance compared to all-organic or all-inorganic TFT circuits. Using integrated pentacene and a-Si:H TFTs we have demonstrated complementary circuits with pA static currents and delay less than 5 sec/stage. Low-temperature and potentially low-cost OTFT and OTFT/a-Si:H TFT circuits, together with the emergence of organic light emitting devices, provide attractive paths to a wide range of low-cost and flexible substrate electronic applications.

2:00 PM, L2 +

Crossover from Band to Hopping Transport in Organic Semiconductors: *Hendrik Schön*¹; Christian Kloc¹; Bertram Batlogg¹; ¹Bell Laboratories, Lucent Tech., Rm. 1E 318, 600 Mountain Ave., Murray Hill, NJ 07974-0636 USA

Charge transport in a variety of organic field-effect transistor materials, such as polyacenes or oligothiophenes, has been investigated in temperature range from 1.7K up to 550K. The molecular orbital overlap and electron-phonon interactions are limiting the charge carrier mobility in these material classes. The mobility increases from approximately 1-5 cm²/Vs at room temperature to several thousand cm²/Vs at low temperatures following a power law for a variety of materials. This behavior is typical for bandlike transport in delocalized states. The effective electronic bandwidth is several hundred meV at low temperatures and decreases due to electron-phonon coupling upon warming. As a result of this band narrowing the residence time of the charge carrier on a molecule increases. Slightly above room temperature this time becomes com-

parable to the intermolecular vibrational relaxation. Hence, the charge carrier becomes localized and the transport mechanism changes to incoherent hopping motion. This is accompanied by an increase of the mobility with temperature and a change of the electric field dependence. Similar crossover phenomena are observed upon doping of pentacene. Furthermore, a strong anisotropy of the charge transport in oligothiophenes has been found and can be explained by the poor molecular orbital overlap across the molecular planes compared to the effective overlap within the planes.

2:20 PM, L3 +

Effects of Doping C₆₀ Fullerene in Diamine and Aluminumquinoline Organic Thin Films on Their Electrical Properties: *Shizuo Fujita*¹; Tadahiro Nakazawa¹; Shigeo Fujita¹; ¹Kyoto University, Elect. Sci. and Eng. Depts., Yoshida, Sakyo, Kyoto 606-8501 Japan

This paper reports a new approach to control electrical properties of organic thin films by doping C₆₀ fullerene, which possesses extremely high electron affinity. The results indicate that the carrier mobility is enhanced in the doped layers, and this enhancement seems to be attributed to strong interaction between the molecular orbitals of organic materials and the C₆₀ molecules. The C₆₀ was doped in diamine (TPD) and aluminumquinoline (Alq₃), which are the most widely used materials for EL devices with codeposition in vacuum evaporation on ITO/glass substrates at the pressure less than 3x10⁻⁷Torr. The source materials were set in separate quartz crucibles, whose temperatures were independently controlled, and the concentration of C₆₀ was controlled by changing the temperature of the crucible. For the C₆₀-doped (5-30%) TPD, it is found that (i) dark conductivity is higher by one to two orders of magnitude than those of both undoped TPD and C₆₀, (ii) PL shows new peaks which are not present both for undoped TPD and C₆₀, (iii) optical absorption properties characteristic to C₆₀ are not observed though the C₆₀ concentration is as high as 30%, and (iv) photoconductivity is enhanced compared to undoped TPD. These results are interpreted as that the carrier (hole) mobility of TPD is enhanced by the C₆₀ doping, rather than the simple carrier hopping among the C₆₀ molecules in TPD, and may be attributed to that the strong electron affinity of C₆₀ molecules effectively interacts with molecular orbitals of TPD, and increases the overlapping of the orbitals between the TPD molecules, resulting in the possibility of carrier transport between the molecules. The enhanced mobility was consistently evidenced from the drain characteristics of the FETs fabricated by C₆₀-doped TPD. The enhancement of conductivity with C₆₀ doping was also observed for Alq₃, together with new PL peaks suggesting the interaction between C₆₀ and Alq₃. The enhanced conductivity of TPD and Alq₃ is apparently promising for lowering the operation voltage of organic EL devices, which may be effective against the degradation.

2:40 PM, L4

Pentacene Thin Film Transistors with Photolithographically Patterned Active Layer: *Chris D. Sherov*¹; Lili Jia¹; David J. Gundlach¹; Hagen Klauk¹; Thomas N. Jackson¹; ¹The Pennsylvania State University, Dept. of Elec. Eng., Ctr. for Thin Film Dev., 121 Elec. Eng. East, University Park, PA 16802 USA

Pentacene organic thin film transistors (OTFTs) have been demonstrated with device performance comparable to amorphous silicon TFTs making them attractive candidates for low-cost, large-area thin film electronics. Ungated pentacene organic semiconductor layers often have a hole accumulation layer at the pentacene/substrate interface which, for unpatterned active layers, can lead to undesirably large leakage between devices. To reduce this leakage current, OTFTs have been fabricated with active layer patterning achieved by depositing the active layer through a shadow mask (sometimes fabricated directly on the OTFT substrate), using a Corbino TFT layout, or by physically removing or 'scratching away' the active layer material around a device. All of these methods have limited utility for large-array or circuit fabrication. Photolithographic patterning of the active layer is of obvious interest, however, the chemicals required for typical photoresist processing can cause structural changes in the organic active layer [1] or other changes that significantly degrade organic device properties. We have developed a photolithographic process using photosensitized polyvinyl alcohol (PVA) for patterning organic active layers without degrading device performance. To demonstrate the utility of the PVA photopatterning, we have fabricated patterned-active-layer pentacene OTFTs. Heavily doped thermally oxidized silicon was used as the substrate, gate electrode, and gate dielectric

for these devices. Palladium source and drain contacts were deposited by ion beam sputtering and photolithographically defined using a lift-off process. A pentacene active layer with 50nm average thickness was deposited by thermal evaporation. A water-soluble PVA film approximately 200nm thick was solution-cast onto the pentacene active layer and used as a negative photoresist. 2 wt% ammonium dichromate was added to the PVA solution as a photosensitizer and water was used to develop the PVA film after UV exposure. The unwanted regions of the pentacene active layer were removed by reactive ion etching in an oxygen plasma. The PVA and pentacene films have comparable etch rates, allowing the PVA layer to be used as an etch mask. A final 5 minute, 100°C hotplate bake was used to remove most of the water remaining in the pentacene film. Devices were tested prior to deposition of the PVA film and after active layer patterning. The field effect mobility in these devices was $\sim 0.3 \text{ cm}^2/\text{V}\cdot\text{s}$ and was unchanged by the active layer patterning. However, off current was reduced from $\sim 100 \text{ nA}$ to $\sim 10 \text{ pA}$ and on/off current ratio increased from $\sim 10^2$ to $> 10^6$ after active layer patterning, demonstrating the effectiveness of this approach for eliminating leakage. PVA photopatterning may be useful for patterning a variety of organic materials and devices. [1] D. J. Gundlach, T. N. Jackson, D. G. Schlom, and S. F. Nelson, *Appl. Phys. Lett.*, vol. 74, p. 3302 (1999)

3:00 PM Break

3:40 PM, L5 *Invited

Recent Progress in Organic and Polymer-Based Thin Film Field-Effect Transistors: Zhenan Bao¹; John Rogers¹; Linda Chen¹; Ananth Dodabalapur¹; Andrew Lovinger¹; Brian Crone¹; Yen-Yi Lin¹; Howard Katz¹; V. Reddy Raju¹; ¹Lucent Technologies, Bell Labs., 600 Mountain Ave. 1A-261, Murray Hill, NJ 07974 USA

Organic thin-film metal-insulator-semiconductor field-effect transistors (MISFETs) are potentially useful in low-cost large area flexible displays and low-end data storage such as smart cards. Much progress has been made recently in discovering new materials, developing low-cost solution-based fabrication processes and realization of large scale integrated complementary circuits. In this talk different semiconducting materials which have been studied for thin film transistors will be reviewed. Specifically, different aspects, which affect the performance of these materials, such as molecular structure, film morphology, and fabrication condition, will be discussed. Orientation of the molecules on the substrate is critical in optimizing charge transport in organic transistors. We have found methods that can macroscopically control both the molecular and crystal growth directions. Anisotropic charge transport was observed and in some cases enhanced mobilities can be achieved. In addition, we will demonstrate the fabrication of plastic transistors and circuits with feature sizes as small as 1 micronmeter using low-cost printing techniques. Finally, large-scale integrated circuits plastic FETs driven display pixels will be presented.

4:20 PM, L6

Field-Effect Conductance Measurements on Microcrystals of Sexithiophene: Anna Chwang¹; Kannan Seshadri¹; Tommie Kelley¹; C. Daniel Frisbie¹; ¹University of Minnesota, Chem. Eng. and Matls. Sci. Depts., 421 Washington Ave. SE, Minneapolis, MN 55455 USA

One of the main objectives of our work has been to elucidate the structure-property relationship of thin organic crystals using field-effect devices. In this talk, we will report recent developments our group has made in the characterization of microcrystals of the organic semiconductor sexithiophene (6T). The crystals typically range in thickness between 2-14 nm and have length and width dimensions of 1-2 μm . The 6T is deposited by vacuum sublimation onto SiO_2/Si substrates pre-patterned with thin (15-20 nm tall, 200-300 nm wide) electrodes. Two types of experiments are conducted in our lab; both are based on a gated transistor format. In one experiment, both source and drain electrodes are fixed and charge transport through the 6T is monitored in air or under vacuum ($\sim 10^{-6}$ Torr). In the other experiment, one or two electrodes are fixed and a conducting AFM probe functions as an additional, positionable electrode. The CPAFM experiments are performed in air. Advantages for the first type of experiment include the ability to compare charge transport through a device between low pressure and atmospheric environments and to conduct temperature (5-300K) and photocurrent (UV-VIS) experiments on the 6T transistors. These measurements can be used to quantify charge injection barriers and to identify charge injection regimes. Advantages for the second approach include the ability to vary

the effective channel length when the CPAFM probe functions as the source or drain electrode and to monitor the potential when the probe functions as a third, monitoring electrode. The latter method is called scanning potentiometry. The CPAFM experiments are used to estimate the organic-metal contact resistance, as well as the resistance associated with defects such as grain boundaries, and to map the local potential over the surface of the organic semiconductor.

4:40 PM, L7

Organic Field Effect Transistors as Vapor Sensors: B. K. Crone¹; A. Dodabalapur¹; A. Gelperin¹; H. Katz¹; Z. Bao¹; L. Torsi²; H. Schon¹; ¹Bell Laboratories, Lucent Tech., 600 Mountain Ave., Rm. 1d-351, Murray Hill, NJ 08823 USA; ²Universita' degli Studi Bari-4, Dept. di Chimica, Via Orabona, Bari I-70126 Italy

Organic semiconducting materials are of interest for applications where conventional inorganic materials are not viable, such as very low cost circuits, or circuits over large areas and on flexible substrates. One concern with organic electronics is their sensitivity to the environment. This sensitivity can be exploited to make organic field effect transistor (FET) vapor sensors. Guillaud and others studied the sensitivity of metallophthalocyanine based chemiresistors to NO_2 . In this work we investigate the response of organic FETs to a variety of volatile organic materials (odors). The experiment consists of looking at the response of several series of organic FETs to a range of odors for a variety of FET bias conditions. The semiconductors include a series in end group length of thermally evaporated oligothiophenes, specifically α -6T, dihexyl α -6T, didodecyl α -6T, and dioctadecyl α -6T. Also considered are soluble regioregular polythiophene polymers, with side groups of either hexyl, dodecyl, or octadecyl. An increase in the end or side group length may increase pathways for odors to diffuse into the semiconductor. We also consider some very well ordered materials such as tetracene, pentacene, CuPc, and F_{16}CuPc . The characteristics of these transistors are measured for odors of various sizes, molecular weights, and functionalities. For example we consider a length series of 1-alcohols, odors with different functional groups (OH, O, or NH_2), and odors with and without ring structures. In an FET the on current, off current, and threshold voltage may react differently to a given set of odors, offering a richer parameter set to distinguish odors than chemiresistors. In general we find semiconductors with longer side or end groups are more sensitive to odor molecules. The on current response can be separated into two regions, first the region where there is a flow of odor, and second after the odor flow is removed. During the odor flow the on current may remain unaffected, decrease, or increase. When the odor flow is removed the on current is either unaffected or reduced to varying degrees. The off current may remain unaffected, decrease or increase upon exposure to an odor. These results are consistent with a simple picture of three possible odor-semiconductor interactions. 1) No interaction. 2) The odor diffuses into the material reducing the order and hence the mobility. 3) The odor interacts with the semiconductor releasing free carriers, increasing the conductivity while the odor is flowing, but also decreasing the order leading to an eventual decrease in mobility. Techniques for further improvement of sensor sensitivity and selectivity are being explored.

5:00 PM, L8 Late News

Session M. Transparent Conducting Oxides - I: Materials and Defect Physics

Wednesday PM Room: Centennial Halls
June 21, 2000 Main Lounge

Session Chairs: Thomas Mason, Northwestern University, Evanston, IL 60208 USA; Len Feldman, Vanderbilt University, Nashville, TN 37235 USA

1:20 PM, M1 *Invited

Comparison of Transparent Conducting Oxides: Roy G. Gordon¹; ¹Harvard University, Depts. of Chem. and Chem. Bio., 12 Oxford St., Cambridge, MA 02138 USA

Transparent conducting oxides (TCOs) are being used for a very wide variety of applications. These include energy-efficient windows in buildings and ovens, defrosters on windows of vehicles and freezers, electrodes for solar cells, displays, and smart mirrors and windows, static dissipation on copiers, and transparent electromagnetic shielding. TCOs have been made from oxides of zinc, cadmium, indium and/or tin by both physical and chemical methods. For each application, the most suitable TCO best meets particular criteria, including optical, electrical, mechanical, chemical and/or economic factors. The differences between these criteria have led to different choices of TCOs for different applications. Fundamental physical constraints on TCOs limit the possibilities for satisfying these criteria much more closely.

2:00 PM, M2

Transparent Conductors in the Ga₂O₃-In₂O₃-SnO₂ System: Doreen Edwards¹; Thomas O. Mason²; ¹New York State College of Ceramics at Alfred University, Sch. of Cer. Eng. and Matls. Sci., 2 Pine St., Alfred, NY 14802 USA; ²Northwestern University, Depts. of Matls. Sci. and Eng., 2225 N. Campus Dr., Evanston, IL 60208 USA

Tin-doped indium oxide, or ITO, is the preferred transparent conductor for device applications because of its high electrical conductivity (>1000 S/cm), high transparency through most of the visible region, and etch-ability. However, materials with higher conductivity and/or higher transparency in the blue-green region of the spectrum are desired for state-of-the-art display devices. One strategy for developing improved materials is to identify novel multication oxides that exhibit transparent conducting behavior. In this work, we report on the subsolidus phase relationships, crystal structures, and electrical properties of phases in the Ga₂O₃-In₂O₃-SnO₂ system. Construction of the subsolidus phase diagram for the ternary oxide system revealed several new phases. One of these phases, expressed as Ga_{3-x}In_{5+x}Sn₂O₁₆, is a transparent conductor with an electrical conductivity of ~ 100 S/cm and optical properties comparable to ITO. While the conductivity of the new phase does not match that of ITO, examination of its structure and defect chemistry provides insights into the electrical properties of a family of In-based transparent conducting oxides that includes In₂O₃, In₄Sn₃O₁₂, and Ga_{3-x}In_{5+x}Sn₂O₁₆. The structure of the new phase was determined using x-ray diffraction, neutron diffraction, and high-resolution electron microscopy. The new phase is similar to indium oxide and In₄Sn₃O₁₂ in that it has an anion-deficient fluorite structure. However, the new phase possesses a tetragonal structure (space group I41a) rather than the cubic bixbyite of In₂O₃ or the rhombohedral structure of In₄Sn₃O₁₂. While Ga_{3-x}In_{5+x}Sn₂O₁₆ and In₄Sn₃O₁₂ contain considerable amounts of Sn as a structural component, the solubility of Sn as an aliovalent dopant is limited to a few tenths of a percent (cation basis), which is considerably lower than the solubility limit of Sn in indium oxide (~ 10% on a cation basis). The difference in Sn solubility is attributed to the nature of the cation sites in the three structures. Specifically, In₂O₃ possesses a highly distorted octahedral cation site that is not present in Ga_{3-x}In_{5+x}Sn₂O₁₆ or In₄Sn₃O₁₂. Nevertheless, electrical property data (conductivity and thermopower vs. pO₂) suggest that low-level Sn-doped Ga_{3-x}In_{5+x}Sn₂O₁₆ has a defect structure similar to ITO, i.e. electrons, isolated Sn

donors, and neutral associates. The implications of common defect structure on this important class of transparent conductors are also discussed.

2:20 PM, M3

Bulk Phase Relations, Electrical, and Optical Properties of Transparent Conducting Oxides in the CdO-In₂O₃-SnO₂ System: Dan R. Kammler¹; Thomas O. Mason¹; Ken R. Poeppelmeier²; ¹Northwestern University, Dept. Matls. Sci. and Eng., 2225 N. Campus Dr. (MLSB), Evanston, IL 60208 USA; ²Northwestern University, Dept. Chem., 2145 Sheridan Rd., #GG35, Evanston, IL 60208 USA

Next generation transparent conducting oxide films used as electrodes in applications such as photovoltaics will require an increased conductivity to decrease sheet resistance to maintain performance as electrode area increases. Raising the conductivity via an increased carrier density will increase absorption from free carriers. Consequently, future transparent conductors must have higher mobilities than those presently in use. Our recent work has focused attention on the CdO-In₂O₃-SnO₂ system because films of cubic (spinel) Cd₂SnO₄ and CdIn₂O₄ have been prepared with high mobility. Cd₂SnO₄ is typically orthorhombic in bulk form^{2,3} and has a substantially lower conductivity than either cubic CdIn₂O₄ or Cd₂SnO₄. This raises the question of whether the bulk cubic spinel solution Cd_{1+x}In_{2-2x}Sn_xO₄ exists, and if so how its electrical and optical properties change across this solution. Phase relations determined between 800 and 1175°C for the vertical section CdIn₂O₄-Cd₂SnO₄ have enabled us to demonstrate that bulk cubic (spinel) Cd₂SnO₄ is metastable and determine that the cubic (spinel) solution Cd_{1+x}In_{2-2x}Sn_xO₄ terminates at x=0.75. Reduced samples in this solution exhibit exceptional four-point dc conductivities exceeding 3500 S/cm (x=0.70). The maximum optical gap estimated from diffuse reflectance spectra is ~ 3.0 eV for 0≤x≤0.15. The optical gap shows negligible change with reduction, possibly because of combined Moss-Burstein and band narrowing effects. Abrupt conductivity increases and optical gap decreases (with increasing x) at specific compositions, i.e. x=0.4 and 0.2 respectively, may be indicative of a change in cation distribution between tetrahedral and octahedral sites. Room temperature thermopower measurements indicate the change in conductivity across the solution is a consequence of an increase in carrier density and that mobility remains relatively constant. The discovery of a large C-type rare earth oxide solid solution In_{2-2x}Cd_xSn_xO₃ (0≤x≤0.40)⁴ in the system ZnO-In₂O₃-SnO₂ and similar chemistry of Zn and Cd raise the question of whether a similar solution (In_{2-2x}Cd_xSn_xO₃) exists in the CdO-In₂O₃-SnO₂ system. Preliminary bulk phase relations determined from powder XRD indicate that the solution In_{2-2x}Cd_xSn_xO₃ (cubic C-type rare earth oxide) extends from x=0 to somewhere between 0.3 and 0.4. The four-point dc conductivity of as-fired samples remains constant near 100 S/cm until x=0.16 at which point it increases sharply to over 1000 S/cm before terminating. Four-point conductivity data of multi-phase samples prepared with an excess of SnO₂ indicate that the solution may contain a small excess of Sn⁴⁺ and be better described by the formula In_{2-x-y}Cd_xSn_yO₃ where y is slightly greater than x. In addition to reporting the Cd_{1+x}In_{2-2x}Sn_xO₄ and In_{2-2x}Cd_xSn_xO₃ solid solutions we also report a preliminary isothermal section (at 1175°C) of the system CdO-In₂O₃-SnO₂ based on powder XRD data from both the single phase solid solution samples and numerous multi-phase samples prepared throughout the rest of the system. References (1)Wu, X.; Coutts, T. J.; Mulligan, W. P. J. Vac. Sci. Technol. A. 1997, 15, 1057-1062. (2)Smith, A. J. Acta. Cryst. 1960, 13, 749-752. (3)Nozik, A. J. Phys. Rev. B 1972, 6, 453-459. (4)Palmer, G. B.; Poeppelmeier, K. R.; Mason, T. O. Chem.Mater. 1997, 9, 3121.

2:40 PM, M4 +

Substitution and Doping Strategies in the In₂O₃ Bixbyite Host Structure: Andrea Ambrosini¹; George B. Palmer¹; Melissa Lane²; Carl R. Kannewurf²; Thomas O. Mason³; Kenneth R. Poeppelmeier¹; ¹Northwestern University, Dept. of Chem., 2145 Sheridan Rd., Evanston, IL 60208-3113 USA; ²Northwestern University, Dept. of Elect. Eng., 2145 Sheridan Rd., Evanston, IL 60208-3118 USA; ³Northwestern University, Depts. of Matls. Sci. and Eng., 2225 N. Campus Dr., Evanston, IL 60208-3105 USA

The structural, electronic, and optical effects of substitution in the bixbyite structure have been investigated. The workhorse transparent conducting oxide (TCO), tin-doped indium oxide (ITO), adopts the cubic bixbyite structure. By isovalently doping the parent indium oxide, it is possible to alter the lattice parameter, band gap, and electrical properties

of the material. Isovalent substitution was achieved in two ways: by replacing In^{3+} with an M^{3+} cation such as Y^{3+} or Sc^{3+} , or by cosubstituting one M^{2+} cation and one M^{4+} cation for a pair of In^{3+} cations, as in the material $\text{In}_{2-2x}\text{Sn}_x\text{Zn}_x\text{O}_{3-8}$, Y_2O_3 and Sc_2O_3 crystallize in the bixbyite structure and form complete solid solutions with In_2O_3 . Solid solutions of $\text{In}_{2-x}\text{M}_x\text{O}_{3-8}$ ($\text{M}=\text{Y}$ or Sc) with varying lattice parameters were prepared and doped with tin. Substitution of tin oxide into $\text{In}_{2-x}\text{Y}_x\text{O}_{3-8}$ results in the formation of the pyrochlore phase, $\text{Y}_2\text{Sn}_2\text{O}_7$, which prevents the tin from donating charge carriers. However, solid solutions in which $\text{M}=\text{Sc}$ could be synthesized and doped with a limited amount of tin oxide without the formation of a second phase. The presence of increasing scandium results in decreasing conductivity with a corresponding increase in the optical band gap and percent transmission as compared to ITO (4% Sn). The decrease in conductivity for the scandium-substituted samples coincides with a decrease in both mobility and carrier concentration in samples containing equal amounts of tin but decreasing ratios of indium vs. scandium. This decrease may be caused by a filling of the electron-donating oxygen vacancies and/or an increase in the formation of neutral tin oxide complexes as the unit cell contracts. An extended cosubstituted solid solution, $\text{In}_{2-2x}\text{Sn}_x\text{Zn}_x\text{O}_{3-8}$ $0 < x \leq 0.2$, in which a $\text{Sn}^{4+}/\text{Zn}^{2+}$ pair isovalently substitutes for two In^{3+} cations in $\text{In}_2\text{O}_{3-8}$ was recently discovered. These materials are not intentionally doped, yet they display relatively high n-type conductivity (up to 600 S/cm). Conductivities in the co-substituted samples decrease with increasing x . Attempts were made to acceptor dope the material by substituting Zn^{2+} for In^{3+} . Up to 4% "excess" Zn^{2+} could be doped into the compound $\text{In}_{1.6}\text{Sn}_{0.2}\text{Zn}_{0.2}\text{O}_{3-8}$ while still maintaining the bixbyite structure, as seen in powder x-ray diffraction and TEM. The samples were annealed in oxygen under high pressure (up to 240 atm) to eliminate compensating anion vacancies and to attempt to fill some of the inherent anion vacancies. The conductivities of the samples decrease significantly after annealing, although Hall measurements indicate that the carriers are still n-type. Hall measurements also show a two-order-of-magnitude decrease in carrier concentrations of the oxidized p-doped samples as compared to the corresponding undoped cosubstituted material. The results imply that many electron carriers have been compensated by holes, although not enough for the material to display overall p-type character.

3:00 PM Break

3:40 PM, M5 *Invited

Nonstoichiometric and Doped Zinc Oxide: *Arthur W. Sleight*¹; ¹Oregon State University, Chem. Dept., 153 Gilbert Hall, Corvallis, OR 97331-4003 USA

Heating white insulating zinc oxide in zinc metal vapors produces an oxygen-deficient red material with increased electrical conductivity. The textbook explanation is that this process has produced interstitial zinc atoms that ionize to give electrons in the conduction band. Such a picture is not supported by our results. We propose instead that the initial reduction of zinc oxide increases conductivity through removal of oxygen from the lattice. The oxygen removed is "extra" oxygen associated with impurities, such as Si, which act as n-type dopants. As a consequence of this process, the color of zinc oxide becomes blue. Further reduction of zinc oxide results in the development of the red color without a further increase in conductivity. We propose that the red color is associated with zinc interstitials that are not ionized. A report in 1961 claimed the interstitial site was occupied at the level of 1.5%. This result was at odds with all other results indicating that the Zn excess never exceeds 0.1%. We have repeated the electron density experiment which confirms an interstitial level of less than 0.1% in red zinc oxide. Doping zinc oxide produces much higher conductivities than nonstoichiometry. Successful dopants include Al, Ga, In, Si, Ge, and F. We have produced much higher conductivities in powders than previously reported. The process employed to achieve the higher conductivities simply takes advantage of entropy at high temperature. Time differential perturbed angular correlation spectroscopy was used to investigate both nonstoichiometric and doped zinc oxide. ⁶⁷Zn NMR studies were conducted on pure and Ga-doped zinc oxide. ⁵⁷Al and ⁶⁹Ga NMR studies were employed for Al- and Ga-doped zinc oxide. Iron Mössbauer studies were conducted on zinc oxide doped with Fe^{2+} and with Fe^{3+} . Iron doping of zinc oxide is not effective for increasing conductivity, but a very unusual site for Fe^{2+} was found. Doped zinc oxide films were prepared by rf magnetron sputtering, using Al, Ga, In, and Ge as dopants. The electrical transport and optical properties of films with different dopant concentrations are compared.

4:20 PM, M6

Defect Physics in ZnO: *S. B. Zhang*¹; Su-Huai Wei¹; Alex Zunger¹; ¹National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

ZnO typifies the class of transparent conducting oxides that can be doped only one way, i.e., n-type. We explain this asymmetry via a study of intrinsic defects including Zn vacancy and interstitial, O vacancy and interstitial, and Zn-on-O antisite, and n-type impurity dopants, ZnO:Al and ZnO:F. We find that ZnO is n-type at Zn-rich conditions. This is because (i) the Zn interstitial is a shallow donor, supplying electrons. (ii) Its formation enthalpy is low for both Zn-rich and O-rich conditions, so this defect is abundant. And (iii) the native defects that could compensate the n-type doping effect, i.e., O interstitial and Zn vacancy, have high formation enthalpies for Zn-rich conditions, so these "electron killers" are difficult to form. We find that ZnO cannot be doped p-type via native defects such as Zn vacancy, despite that they are shallow. This is because at both Zn-rich and O-rich conditions, the defects that could compensate p-type doping (i.e., O vacancy, Zn interstitial, and Zn-on-O antisite) have low formation energies so these "hole killers" form readily. In addition, we found that both neutral and (1+) charged O vacancies are deep, not shallow as many had expected. The single electron a_1 level is about 1.0 eV below the conduction band minimum (or 2.4 eV above the valence band maximum) occupied by either 2 or 1 electrons. Based on the results, we suggest that O vacancy is the source of green luminescence in ZnO. Interestingly, the doubly charged O vacancy (in which the a_1 level is empty) undergoes a large outward breathing-mode structural relaxation. A long carrier-lifetime, non-radiative decay model based on the capture of two holes by the O vacancy is thus proposed to explain the observed persistent photoconductivity in ZnO.

4:40 PM, M7 +

Cation Distribution in the Transparent Conducting Oxide $\text{Cd}_{1-x}\text{In}_x\text{Sn}_x\text{O}_4$: *Donggeun Ko*¹; Kenneth R. Poeppelmeier¹; Daniel R. Kammler²; Luke N. Brewer²; Vinayak P. Dravid²; Thomas O. Mason²; ¹Northwestern University, Chem. Dept., 2145 Sheridan Rd., Evanston, IL 60208 USA; ²Northwestern University, Matls. Sci. and Eng. Depts., 2145 Sheridan Rd., Evanston, IL 60208 USA

Next generation transparent conducting oxides used as electrodes in devices such as photovoltaics and flat panel displays require an increased conductivity to maintain device performance as the electrode area increases. If carrier density is increased transparency will suffer as a result of free carrier absorption. Therefore, mobility must be increased to preserve transparency and increase conductivity. Both CdIn_2O_4 and Cd_2SnO_4 have been prepared in cubic (spinel) thin film form and found to have high mobilities. Bulk phase equilibrium studies reveal a large solid solution of spinel $\text{Cd}_{1-x}\text{In}_{2x}\text{Sn}_x\text{O}_4$ ($0 < x < 0.75$ at 1175°C) between bulk orthorhombic Cd_2SnO_4 and cubic (spinel) CdIn_2O_4 . The conductivity of reduced samples prepared along the solution line is nearly constant at 2200 S/cm up until $x=0.4$ at which point it increases markedly to 3500 S/cm at $x=0.6$ and the n remains nearly constant until the solution terminates at $x=0.75$. We believe this may signal a sudden change in cation distribution at or near the $x=0.4$ composition. We have investigated the cation distribution in a bulk CdIn_2O_4 specimen (prepared using ¹¹²CdO) quenched from 1175°C and 1000°C via Time of Flight (TOF) neutron diffraction and X-ray diffraction. The TOF data were collected at the Intense Pulsed Neutron Source at Argonne National Laboratory. X-ray data were collected on a Scintag XDS 2000 diffractometer using Cu K α radiation. Rietveld analysis was conducted in a combined manner of neutron and X-ray diffraction using the Generalized Structure Analysis System (GSAS). Although their X-ray scattering factors (Cu K α) are too close to practically distinguish them, the neutron scattering cross sections of ¹¹²Cd and In are 6.9 and 2.62 barns, respectively. Thus, they are distinguishable by neutron diffraction. Preliminary results reveal that the cation distribution is near random in CdIn_2O_4 (i.e. 66% of the tetrahedral and octahedral sites are occupied by In^{3+} cations and the remainder of each site is occupied by ¹¹²Cd²⁺ cations) at 1175°C. The TEM technique of Atom Location by Channeling Enhanced Microanalysis (ALCHEMI) was used to study the cation distribution of quenched samples prepared along the solution line $\text{Cd}_{1-x}\text{In}_{2x}\text{Sn}_x\text{O}_4$ at 1175°C. ALCHEMI involves setting up dynamical diffraction conditions in a crystallite in which the electron Bloch Wave is localized on specific atomic planes (in this case the octahedral and tetrahedral (400) planes). The resulting energy dispersive x-ray spectroscopy (EDX) spectra can then be used to determine the cation distribution in

that crystallite. Preliminary results from ALCHEMI showed crystallites of primarily normal CdIn_2O_4 in contradistinction to the Rietveld Analysis. The distribution of Cd^{2+} and In^{3+} cations appears to remain approximately constant (i.e. Cd^{2+} is confined to tetrahedral sites and In^{3+} to octahedral sites) as x increases. The Sn^{4+} appears to occupy the octahedral sites. In addition to presenting these results we will propose a thermodynamic and kinetic picture of the cation distribution in CdIn_2O_4 derived from these data.

5:00 PM, M8

Atomic Chemical Potential Dependence of the Structural and Doping Properties of Cadmium Stannate (Cd_2SnO_4): *Su-Huai Wei*¹; S. B. Zhang¹; ¹National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

For ternary compounds, it has been established that equilibrium growth is defined by two independent parameters known as the atomic chemical potentials. In the case of cadmium stannate, these are the energies of Cd and Sn in their respective reservoirs varying over a triangle determined by the precipitation of Cd and Sn metals, and by the co-existence of Cd, Sn, and O sources with cadmium stannate. However, secondary phases may form within the triangle that puts additional thermodynamic restrictions on the growth of the compound. For cadmium stannate, (i) the calculated CdO and SnO_2 phases occupy a majority part of the triangle, effectively shrinking the stable cadmium stannate phase region into a narrow line. This explains why the growth of cadmium stannate can be difficult and provides the first theoretical insights on how to optimize the growth conditions. (ii) We further determined that cadmium stannate has the inverse spinel structure (where Sn is on the octahedral sites only, but Cd is on both the tetrahedral and octahedral sites), not the normal structure (in which Sn occupies only the tetrahedral sites and Cd occupies only the octahedral sites). Because Cd and Sn have similar atomic numbers, and because Sn isotopes have no quadruple moment, a structure determination by either X-ray or by Mossbauer spectroscopy is difficult and inconclusive for this compound. Our first-principles calculations showed conclusively that the inverse structure, being 0.74 eV/ Cd_2SnO_4 lower in energy, is more stable. (iii) We then calculated the formation energies of cadmium and oxygen vacancies and Sn-on-Cd antisite. The Cd vacancy acts as shallow double acceptor while both O vacancy and Sn-on-Cd antisite act as double donors. The antisite has significantly smaller formation energy than the O vacancy and its defect transition energy level is shallow. Hence in cadmium stannate, O vacancy is not the main cause of n-type as many believed but Sn-on-Cd antisite is.

Session N. Epitaxy for Devices

Thursday AM Room: Driscoll Center North
June 22, 2000 Ballroom A/B

Session Chairs: Mike Tischler, Epitronics, Mesa, AZ 85210 USA; Ray Tsui, Motorola, Inc., Tempe, AZ 85284 USA

8:00 AM, N1 +

Observation of Saturation Effects of As Precipitates in Large-Area MBE-Grown ITG-GaAs MSM-Photodetectors: *Vijay Krishnamurthy*¹; Marian C. Hargis¹; Michael R. Melloch¹; David T. Mathes¹; ¹Purdue University, Sch. of Elect. and Comp. Eng., West Lafayette, IN 47907-1285 USA

Low temperature growth of GaAs by molecular beam epitaxy has been studied extensively since 1988. Low temperature growth incorporates excess arsenic in the crystal and with anneal, this excess arsenic coarsens and precipitates. Several models have been proposed to account for the properties of this material, the most important among these being the defect model and the buried Schottky barrier model. Both these models have had reasonable success in explaining some of the electrical properties of the material. In a typical normal temperature grown GaAs detector, the responsivity decreases as you increase the incident light intensity. This is because, at higher light intensities, carrier pile-up occurs at

the contact due to the increased rate of carrier-generation. This carrier-crowding tends to screen out the electric-field as well as increases carrier-scattering and consequently the responsivity reduces. However, the devices reported in this paper show atypical photoresponse curves. The device structure of the samples in this study was reported previously. In order to examine the effects as a function of precipitate density, various structures were grown in the temperature range of 300°C to 450°C. The devices in the middle of this range had a responsivity of 0.3 A/W at 10V bias and low light intensities (<100 microwatts). As you increase the light intensity, the responsivity decreases at first, as you would expect for a typical device. But as you increase the light intensities further (>100 microwatts), the responsivity starts increasing again. This effect has been observed before in abrupt heterojunction InGaAs MSM-PDs. In these devices, the increase in responsivity is attributed to the increase in thermionic emission over the heterojunction at higher light intensities. In our present case, each of the As precipitates can be thought of as a buried Schottky barrier with an abrupt interface. The observed initial decrease in responsivity is due to field-screening resulting from charge pile-up and recombination at these precipitate sites. At higher light intensities, the recombination rate at these sites saturates and the rate of carrier emission increases. This would lead to an increase in responsivity as is observed in these devices. In effect, we could say that the recombinative effect of the As-precipitates get washed out at higher light-intensities and the device behaves like a typical GaAs MSM-PD. Thus, this work could pave the way for a novel method in measuring the recombinative capacity of an As precipitate in ITG-GaAs. It could also shed new light on the recombinative mechanism at these defect-sites and one could gain a new understanding of ITG-GaAs and their applications to MSM-PDs.

8:20 AM, N2 +

Growth and Characterization of InAlGaP Lasers with Native-Oxide Optical and Carrier Confinement: *Richard D. Heller*¹; Min-Soo Noh¹; Yuichi Sasajima¹; David A. Kellogg²; Nick Holonyak²; Russell D. Dupuis¹; ¹The University of Texas at Austin, Microelect. Rsch. Ctr., PRC/MER-R9900, Austin, TX 78712-1100 USA; ²University of Illinois at Urbana-Champaign, Ctr. for Comp. Semiconduct. Microelect., 208 N. Wright St., Urbana, IL 61801 USA

$\text{In}_{0.5}(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{P}$ is widely used in visible wavelength laser diodes and high-brightness LEDs. Much of the research on $\text{In}_{0.5}(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{P}$ laser diodes has been focused on practical red and visible lasers as well as improving the device performance for uses in laser printing and optical storage devices. However, poor electron confinement in $\text{In}_{0.5}(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{P}$ heterostructures and problems achieving high acceptor levels in p-InAlP have limited the high temperature and high power operation as well as the device performance such as threshold current in laser diodes. We have explored the use of native-oxide top- and bottom-confined narrow stripe p-n $\text{Al}_y\text{Ga}_{1-y}\text{As}/\text{In}_{0.5}(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{P}$ quantum-well heterostructure (QWH) lasers to improve device characteristics. This laser diode is a modified mesa QWH laser that is defined and confined by laterally oxidized high Al-composition $\text{Al}_y\text{Ga}_{1-y}\text{As}$ layers on both the p- and n-side of the layered structure. This structure provides excellent current and optical confinement. These structures were grown by low-pressure MOCVD in a modified EMCORE GS3200 UTM reactor at a pressure of 60 Torr using trimethylindium, trimethylaluminum, triethylgallium, AsH_3 , and PH_3 as sources and purified H_2 as a carrier gas. Diethylzinc and bis(cyclopentadienyl) magnesium were used as the Zn and Mg p-type dopants, respectively, and disilane was used as the Si n-type dopant. The lattice matching conditions for the AlGaAs, InGaP, InAlP, and InAlGaP alloys were established using X-ray rocking curve and photoluminescence characterization of about 500nm thick layers. The free carrier concentration and doping levels were measured by electrochemical capacitance-voltage profiling. These structures were grown at 650°C simultaneously on GaAs:Si substrates. The native-oxide defined $\text{In}_{0.5}(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{P}$ QWH laser design consists of the following layers: 250nm GaAs:Si buffer layer, 300nm $\text{Al}_y\text{Ga}_{1-y}\text{As}$:Si oxidizable layer, 300nm $\text{In}_{0.5}\text{Al}_{0.5}\text{P}$:Si cladding layer, 100nm $\text{In}_{0.5}(\text{Al}_{0.6}\text{Ga}_{0.4})_{0.5}\text{P}$:ud waveguide, two 8nm $\text{In}_{0.5}\text{Ga}_{0.5}\text{P}$:ud quantum wells with a 10nm $\text{In}_{0.5}(\text{Al}_{0.6}\text{Ga}_{0.4})_{0.5}\text{P}$:ud barrier, 100nm $\text{In}_{0.5}(\text{Al}_{0.6}\text{Ga}_{0.4})_{0.5}\text{P}$:ud waveguide, 300nm $\text{In}_{0.5}\text{Al}_{0.5}\text{P}$:Mg or Zn cladding layer, 300nm $\text{Al}_y\text{Ga}_{1-y}\text{As}$:Mg or Zn oxidizable layer, and 100nm GaAs:Mg or Zn contact layer. Then, a mesa is selectively etched to the GaAs buffer layer, and the sample is placed in an oxidation furnace to laterally oxidize the high Al-composition AlGaAs layers above and below

the active region to form native-oxide optical and carrier confinement layers. The broad-area diodes lased under pulsed conditions at threshold current densities from 500-1000 A/cm² at wavelengths from 630 to 650 nm. The native-oxide defined narrow-stripe InAlGaP devices also lased under pulsed operation conditions at a threshold of 1000 A/cm². Furthermore, the native-oxide defined InGaP laser lased CW under optical excitation at 300K, which we believe to be the first demonstration of an InAlGaP laser structure having a dual native-oxide aperture. We will report the growth, characterization, and lasing properties of these structures.

8:40 AM, N3

Comparison of Different Sources for Carbon Doping in the GaAs Base Layer of Heterojunction Bipolar Transistors Grown by LP-MOVPE: *T. Bergunde*¹; *E. Richter*¹; *P. Kurpas*¹; *M. Achouche*¹; *J. Würfl*¹; *M. Weyers*¹; *F. Brunner*¹; ¹Ferdinand-Braun-Institut für Höchstfrequenztechnik, Matls. Tech. Dept., Albert-Einstein-Str. 11, Berlin D-12489 Germany

Carbon has become the dopant of choice for the GaAs base layer of Heterojunction Bipolar Transistors (HBTs). This is attributed to the high solubility as well as low diffusivity in GaAs, enabling p-type doping levels above 10¹⁹ cm⁻³ confined to specific device regions. However, obtaining good minority carrier transport characteristics in carbon-doped layers to achieve state-of-the-art performance in bipolar devices is not straightforward. Accordingly considerable differences in the achieved HBT current gain at a given base sheet resistance have been reported in literature. In this work we compare different carbon doping techniques in terms of growth-related material and HBT device properties. Carbon doping up to 6x10¹⁹ cm⁻³ was achieved either via trimethylgallium (TMG) and arsine (AsH₃) only, adding the extrinsic carbon source carbontetrabromide (CBr₄) or using TMG and trimethylarsenic (TMAs) as precursors. Growth was carried out in an AIX2400G3 multiwafer MOVPE reactor (5x4") using H₂ as carrier gas. It is found that intrinsic carbon doping above 1x10¹⁹ cm⁻³ requires V/III ratios near unity either using AsH₃ or TMAs. The replacement of AsH₃ by the organometallic TMAs enhances carbon incorporation, but using higher V/III ratios results in surface defects and reduced Hall mobilities. Thus, intrinsic carbon doping is in principle restricted to a small parameter range, where growth rate and doping homogeneity are limited by the group V supply. The carbon source CBr₄ gives the advantage of more flexibility in the choice of growth parameters since here carbon incorporation primarily depends on the halomethane supply. However, optimization of epitaxial growth results in comparable structural and morphological layer properties for all investigated doping techniques. Results of SIMS, X-ray diffraction and Hall measurements indicate a complete substitutional incorporation of carbon on the As lattice site independent of doping method. Employing different base growth conditions GaInP/GaAs-HBT structures were processed in a dry-etched process with ledge technology to assess device performance. DC measurements on large area HBTs reveal distinct differences in device characteristics depending on doping method. We define the ratio of maximum current gain to base sheet resistance β/R_{sb} in order to evaluate base transport properties which are limited by various recombination mechanisms. It is found that the highest β/R_{sb} values (around 0.5 for $d_{base}=110$ nm and $p_{base}=3 \times 10^{19}$ cm⁻³) are obtained using TMG and AsH₃ as precursors. Replacing the hydride by TMAs results in much lower β/R_{sb} values (~0.3) at the same base thickness and doping level. The use of CBr₄ also leads to reduced β/R_{sb} values in a broad range of base growth parameters. Measured emitter-base diode idealities are near unity for all base doping methods indicating comparable emitter injection efficiencies. We suggest that the differences found are due to a varying type or density of Shockley-Read-Hall recombination centers depending on base growth conditions or precursors, respectively.

9:00 AM, N4 +

Bandgap Engineering via the Insertion of Strained Al_{0.7}In_{0.3}As Emitter Layers in Abrupt n-p AlInAs-GaInAs Heterojunction Diodes and Heterojunction Bipolar Transistors: *Changhyun Yi*¹; *April S. Brown*¹; *Robert A. Metzger*¹; ¹Georgia Institute of Technology, Sch. of Elect. and Comp. Eng., 791 Atlantic Dr., Microelect. Rsch. Ctr., Atlanta, GA 30332-0269 USA

Herein, we investigate the effects of inserting a strained Al_{0.7}In_{0.3}As layer in a composite emitter layer of AlInAs-GaInAs HBTs. The effects of strained layer thickness and position are studied by comparing diode

ideality factors η and turn-on voltages V_{BE} . HBT Gummel characteristics and C-E offset voltage V_{CEoff} . The objective of this effort is to improve device gain by increasing the valence band discontinuity ΔE_v , while understanding the concurrent modification of other device characteristics. The experimental results are compared to simulation results achieved with a physically-based device model. The structures were grown by solid source MBE. The base doping was 2×10^{19} cm⁻³. The composite emitter consists of a lattice-matched layer, a strained emitter (Al_{0.7}In_{0.3}As) layer, and an additional lattice-matched spacer layer. The insertion of a pseudomorphic Al_{0.7}In_{0.3}As layer increases both the conduction band discontinuity ΔE_c , as well as ΔE_v . We varied the thickness and position of the strained layer to understand the effects of 1) band-structure modification, 2) the possible introduction of traps and/or interface states, and 3) the possible modification of Be diffusion due to the strain. For the diodes, the position of the strained layer from the GaInAs was varied from 0 to 40 nm, and the thickness was varied from 0 to 30 nm. The V_{BE} are varied from 0.8 to 0.61 V. As the strained layer is moved away from the junction, the V_{BE} decreases, as simulated, due to a reduction of the effective ΔE_c at the junction. The η of the diode varies from 1.29 to 1.5, with the highest value obtained for the structure with no spacer layer, as expected due to highest ΔE_c at the heterojunction. A reduction in V_{BE} and increase in η is observed as the thickness of the strained layer is increased above 15 nm due to the introduction of defects in the strained layer. HBTs were grown and fabricated based on the characteristics of the diode structures. We analyzed a lattice-matched control structure, as well as two composite emitter HBTs with 15 nm strained layers. A significant improvement in gain was observed for both HBTs with composite emitters. The control sample had a gain of 34, while a structure with no spacer had a gain of 40, and a structure with a spacer had a gain of 48. In addition, the collector and base ideality factors were improved for the composite emitter structure with the spacer (1.3 and 1.2, respectively), and reflect expected changes in transport physics from a high abrupt junction to an effective "step-graded" junction. These results show a new approach to modifying device characteristics in HBTs. In addition, simulation of the structures allows of a better understanding of the role of extrinsic and intrinsic material characteristics on HBT performance. This work was supported by the NSF (ECS- 9633535).

9:20 AM, N5

Growth Temperature Dependence of 1.5 μ m Photoluminescence from β -FeSi₂ Balls in Si and Realization of Electroluminescence Nearly at Room Temperature: *Takashi Suemasu*¹; *Yusuke Iikura*¹; *Yoichiro Negishi*¹; *Ken-ichiro Takakura*¹; *Fumio Hasegawa*¹; ¹University of Tsukuba, Instit. of Appl. Phys., 1-1-1 Tennohdai, Tsukuba, Ibaraki 305-8573 Japan

β -FeSi₂ is attracting much attention because of its direct band gap of about 0.83eV at room temperature (RT). β -FeSi₂ has been fabricated mostly by ion beam synthesis (IBS), and thus a strong quenching of the photoluminescence (PL) and electroluminescence (EL) signals due to a large concentration of defects prevented RT light emission from β -FeSi₂. In place of IBS, we have fabricated Si/ β -FeSi₂ balls/Si structures by MBE; however, the PL intensity was weak. In this work, we found that the 1.5 μ m PL intensity from β -FeSi₂ balls embedded in Si by MBE depended strongly on the Si MBE growth temperature for embedding β -FeSi₂. Clear EL was realized nearly at RT using the optimum growth condition. Si/ β -FeSi₂ balls/Si structures were fabricated as follows: First, a 10nm-thick β -FeSi₂ epitaxial layer was grown on n-Si(100) by Fe deposition at 470°C. Next, 60min annealing was performed at 850°C in order to improve the β -FeSi₂ crystalline quality. Then a 200nm-thick undoped Si layer was grown by MBE to embed the β -FeSi₂ in Si. During the above fabrication process, the β -FeSi₂ film aggregated into 0.1 μ m-diameter β -FeSi₂ balls in Si. We prepared several samples with β -FeSi₂ embedded in Si at different temperatures of 400-750°C. Finally, all the samples were annealed in Ar at 900°C for 14h. PL measurements at 77K revealed that the 1.5 μ m PL intensity increased with decreasing the Si MBE growth temperature. The PL peak intensities of the samples with β -FeSi₂ embedded in Si at 630°C, 500°C and 400°C were about 2, 12 and 13 times larger than that embedded at 750°C, respectively. We observed a significant difference in reflection high-energy electron diffraction patterns at the initial embedding stages between the samples. The samples with β -FeSi₂ embedded at 400°C and 500°C showed a clear Si spotty pattern, and gradually changed to a 2x1/1x2 Si streaky pattern as the Si MBE growth proceeded, whereas those embedded at 630°C and 750°C showed the streaky pattern from the

beginning. It is reported that the electronic structure of β -FeSi₂ is highly sensitive to modification of the lattice parameters. We therefore suppose that such differences in the initial growth stage led to difference in the presence of strain induced in the β -FeSi₂ balls. A detailed analysis of the lattice parameters is now under investigation. Based on the above results, we chose 500°C for the embedding temperature of β -FeSi₂ in Si by MBE, and fabricated a p-Si/ β -FeSi₂ balls/n-Si light emitting diode structure. We used a high resistive FZ n-Si substrate, and thus current injection was difficult at low temperatures; however, we observed clear EL at 240K, peaking at a wavelength of 1.6 μ m and having an FWHM of 60meV under a forward current of 6Ac^m-2.

9:40 AM Break

10:20 AM, N6 +

Electrical Properties of InGaAs/InP Composite-Channel Modulation-Doped Structures Grown by Solid Source Molecular Beam Epitaxy: *Tong-Ho Kim*¹; April S. Brown¹; Robert A. Metzger¹; ¹Georgia Institute of Technology, Elect. and Comp. Eng. Depts., 791 Atlantic Dr., Atlanta, GA 30332-0269 USA

We report on an investigation of the effects of structural design parameters, such as channel thickness, the inclusion of hole barriers, Al-rich Schottky barriers, and various doping profiles, on the properties of InGaAs/InP composite-channel modulation-doped structures. The goal of the effort is to maximize channel conductivity, while maximizing the InP content in the channel, to maximize on-state breakdown and drain current. To the best of our knowledge we have achieved the highest channel conductivity in a composite channel structure. For a 20 nm InGaAs/15 nm InP channel with delta-doping, we have achieved a 300K 2DEG density of 4.3×10^{12} cm⁻² and mobility of 10,300 cm²/Vs at 300K. The influence of the InP doping approach in the subchannel has been thoroughly investigated. We have assessed undoped subchannels, uniformly doped subchannels and delta-doped subchannels. The mobility of the structures with delta-doped subchannels depends critically on the spacer layer thickness. As the InP spacer thickness is reduced from 15 nm to 4 nm, the 2DEG density increases to 4.9×10^{12} cm⁻² due to improved transfer efficiency. However, the electron mobility decreases to 18,000 cm²/Vs at 77K due to an increase in remote impurity scattering. The InGaAs channel thickness was varied from 0 to 20 nm, while maintaining a constant total channel thickness of 50 nm. The electron mobility is fairly insensitive to the InGaAs channel thickness in the range of 5 to 20 nm, with a very high mobility of 11,016 cm²/Vs achieved for the thinnest channel; however, when the InGaAs channel thickness is less than 5 nm, the 300K mobility is degraded by > 30 %. In our results, the best mobility was obtained with a 5 nm thick InGaAs channel. This results from a design trade-off between the InGaAs thickness and the 2DEG conductivity in exploiting quantum size effects. The optimum thickness, placement and composition of an InGaP hole barrier were investigated. The conductivity of a structure with a 2.5 nm In_{1-x}Ga_xP (0 < x < 0.5) hole barrier inserted between the channel and donor layer decreased in comparison to a control. This can be attributed to interface roughness at the InGaP/InGaAs interface. For this design, the thickness of the spacer layer is effectively increased. By placing the hole barrier above the donor layer, we recover the original 2DEG characteristics the InGaAs/InP composite-channel MD structures grown without an InGaP hole barrier. In a 0.15 μ m-gate InGaAs/InP composite-channel HEMT, a drain current density of 830 mA/mm was measured at a 4.4 V. A maximum transconductance of 730 mS/mm was obtained at the gate voltage of 0.25 V. The InGaAs/InP composite-channel HEMT not only showed excellent DC characteristics, but also has demonstrated state-of-the-art RF performance at W-band. We would like to acknowledge the support of DARPA MAFET3 Contract N66001-96-C-8629 and NSF ECS 9633535.

10:40 AM, N7

InAsSb as a Channel Material in High Electron Mobility Transistors: *Brian R. Bennett*¹; Ming-Jey Yang¹; J. Brad Boos¹; W. J. Moore¹; ¹Naval Research Laboratory, Code 6876, 4555 Overlook Ave. SW, Washington, DC 20375-5347 USA

Low-voltage, low-power-consumption electronics will be critical in future high-speed analog and digital applications that require lightweight power supplies, long battery lifetimes, improved efficiency, or high component density. AlSb/InAs-based HEMTs are potential candidates for these applications due to the high mobility, velocity, and sheet charge density that can be obtained in this material system. An obstacle to the

development of useful InAs/AlSb HEMTs is the relatively large leakage current. [Boos et al., Trans. Electr. Dev. 45, 1869 (1998)] The addition of Sb to the InAs channel changes the band structure from a staggered type-II heterojunction to a type-I. The existence of hole barriers on both sides of the quantum well, not present in the type-II lineup, enables the confinement of holes which are generated thermally or as a result of impact ionization in the channel. As a result, the holes can be more effectively drained to the source contact rather than having them move into the AlSb buffer layer where they are likely to cause deleterious trapping effects or be collected at the gate contact and thereby increase the gate leakage current. Samples were grown by solid-source molecular beam epitaxy. The composition control of ternary alloys containing two anions is difficult. For this reason, we grew the InAs_{1-x}Sb_x channels using a digital alloy. For example, to achieve a 150 Å layer equivalent to InAs_{0.8}Sb_{0.2}, the growth sequence was ten repeats of: 4 monolayers (ML) InAs/1 ML InSb. X-ray diffraction measurements of thicker digital alloy layers revealed superlattice satellites and showed that good composition control could be achieved for growth temperatures near 400°C. Higher temperatures result in less incorporation of Sb due to evaporation. To confirm the type-I alignment between AlSb and InAs_{1-x}Sb_x, we carried out PL measurements at 5K with a Fourier transform infrared spectrometer. In contrast to the weak luminescence from AlSb/InAs single quantum wells, samples with x > 0.15 exhibit strong luminescence, consistent with a type-I band structure. A heterostructure containing a 150 Å InAs_{0.8}Sb_{0.2}/AlSb quantum well was grown on a GaAs(SI) substrate. The 300K mobility was 13,000 cm²/V-s, with a sheet carrier concentration of 1.4×10^{12} /cm². HEMTs with 0.1 μ m gate length exhibit decreased output conductance and improved voltage gain compared to InAs-channel HEMTs. At V_{DS}=0.6V, a microwave transconductance of 700 mS/mm and an output conductance of 110 mS/mm were obtained, corresponding to a voltage gain of 6. The mobility of the InAs_{0.8}Sb_{0.2} HEMT is only about half the value typically obtained for InAs/AlSb HEMTs. We found that the lower growth temperature (400 vs. 500°C) is the reason. An additional sample with an InAsSb channel was grown at 500°C as a true alloy (i.e. no digital superlattice). PL measurements showed that the composition was InAs_{0.8}Sb_{0.2}. The resulting room-temperature mobility was 26,000 cm²/V-s, suggesting that even better HEMT performance is possible.

11:00 AM, N8 +

Facet-Free Raised/Source Drain Contacts for Dual-Gate MOSFETs by Selective Epitaxy: *Thomas A. Langdo*¹; Anthony Lochtefeld²; Andrew Wei²; Dimitri A. Antoniadis²; Eugene A. Fitzgerald¹; ¹Massachusetts Institute of Technology, Dept. of Matls. Sci. and Eng., Cambridge, MA 02139 USA; ²Massachusetts Institute of Technology, Depts. of Elect. Eng. and Comp. Sci., Cambridge, MA 02139 USA

The double-gate (DG) MOSFET is a prime candidate for sub-100 nm gate length Si CMOS. However, realization of the ideal DG-MOS structure involves significant technological challenges: formation and alignment of gates above and below a thin single-crystalline silicon layer, and achieving low source/drain resistance for this thin layer. For ultimate scalability, the silicon channel must be on the order of 10-15 nm thick—too thin for silicidation of the source/drain regions. We employ selective epitaxy to thicken the source and drain by \approx 50 nm, thus allowing easy silicidation and a low series resistance. To realize these advantages we have developed a facet-free selective epitaxy process combining ultra-high vacuum chemical vapor deposition (UHVCVD) and RIE (reactive ion etched) LTO (low temperature oxide) spacers for electrical isolation of the source/drain from the gate. This process relies upon the use of doping to control facet formation during selective growth and proper post-RIE cleans to remove Si surface fluorocarbon residue from the spacer RIE that can inhibit subsequent selective Si growth. Recently, low pressure facet-free epitaxy has been achieved by utilizing vertical Si₃N₄ spacer sidewalls or by controlling the sidewall profile by combinations of Si₃N₄ overhangs on thin SiO₂ liners. We report the achievement of facet-free epitaxy by moderate PH₃ doping of SiH₂Cl₂/H₂ at 750°C without the addition of Cl₂ or HCl to suppress Si facet formation adjacent to reactive ion etched SiO₂ spacers. This process relies upon a combination of doping and the SiO₂ spacer sidewall profile to control facet growth. The source/drain doping level necessary during growth is 1×10^{18} /cm³ n-type which can then easily be ion implanted n- or p-type to 1×10^{20} /cm³ for both NMOS and PMOS applications. Facet development against both wet-etched and dry-etched oxide spacers will be compared. Raised source/drain results of dual gate devices on SOI wafers will be presented. The

LTO spacer patterning is performed in an radio frequency magnetically coupled Applied Materials Precision 5000 Etcher with an CHF_3/O_2 gas mixture ($\text{CHF}_3:\text{O}_2=30\text{ sccm}:3\text{ sccm}$) operating at 350W RF and 100mTorr. The influence of various post-RIE treatments on selective growth morphology (piranha etch, UVO_3 clean, resist ash, O_2 plasma, and growth of a thin sacrificial oxide and dilute HF dip) combined with overetch times from 0 to 5 seconds have been investigated. Excellent selective Si growth morphology is obtained with the use of short overetch times between 0 to 3 seconds and either a resist ash or growth of a thin sacrificial oxide and subsequent HF dip step, confirming elimination of the RIE fluoropolymer layer. This process has wide ranging application to both SOI and bulk Si technologies for fabrication of low-resistance contacts in advanced devices.

11:20 AM, N9

Resonant Interband Tunneling Diodes with AlGaSb Barriers: *Richard Magno*¹; Allan S. Bracker¹; Brian R. Bennett¹; Mark E. Twigg¹; ¹Naval Research Laboratory, Elect. Matls. Brnch., Code 6876, Washington, DC 20375-5347 USA

Resonant interband tunneling diodes (RITD), InAs/AlSb/GaSb/AlSb/InAs, have high peak current densities ($>10^4\text{ A/cm}^2$) and peak-to-valley ratios (>15) which make them good candidates for applications in high frequency, low power digital electronics. To improve the peak current density, structures using barriers composed of $\text{Al}_{1-x}\text{Ga}_x\text{Sb}$ in place of AlSb have been tested. $\text{Al}_{1-x}\text{Ga}_x\text{Sb}$ alloys have a narrower band gap than AlSb, and this is expected to increase the peak current density. A series of test devices were prepared by molecular beam epitaxy. InAs substrates were used to minimize the lattice mismatch between the substrate and the RITD layer structure. The growth procedures included using InSb interface bonds at the AlSb/InAs interfaces. Photolithography and wet etching were used to form mesa diodes with nonalloyed Ti/Pt/Au ohmic contacts, which ranged from 2 to 50 μm in diameter. Point contact procedures were used to measure the current voltage characteristics at room temperature. Diodes with $x=0.1$ were found to have peak current densities as much as three times larger than those with $x=0.0$. Similar peak to valley ratios were found for the $x=0.0$ and $x=0.1$ diodes. The increase in the current density reported above also aids in understanding another phenomenon found in InAs/AlSb/GaSb/AlSb/InAs diodes grown with the same thickness for both AlSb barriers. The ratio of the peak current measured with a positive bias to that for a negative bias, I_{p+}/I_{p-} is often less than one, which indicates an asymmetry in the MBE layer structure. This ratio has been found to depend on the substrate temperature used during the growth with smaller values found for the higher temperature growths. Ga segregation from the GaSb well into the top AlSb barrier can account for this behavior as it will result in an $\text{Al}_{1-x}\text{Ga}_x\text{Sb}$ top barrier with a higher tunneling probability than the AlSb barrier under the well. The trend to smaller values of I_{p+}/I_{p-} for diodes prepared during a 500°C high temperature growth compared to a growth at 350°C is consistent with more segregation occurring at the higher temperature. Ga segregation has been reported in Raman measurement studies of the growth of AlSb self assembled quantum dots on GaAs substrates¹. In summary, RITD devices with $\text{Al}_{1-x}\text{Ga}_x\text{Sb}$ barriers have been tested and found to have higher peak current densities than devices with AlSb barriers, with little deterioration in the peak to valley ratio. Ga segregation from the GaSb well into the AlSb barrier on top of the well can explain the reduction in the ratio I_{p+}/I_{p-} found when growing diodes at high substrate temperatures.

11:40 AM, N10

Lattice Rotation Determination in MHEMT Structures by High Resolution X-Ray Diffraction: Abbas Torabi¹; *Peter S. Lyman*¹; T. D. Kennedy¹; P. J. Lemonias¹; E. J. Yarranton¹; W. E. Hoke¹; ¹Raytheon RF Component, 362 Lowell St., Andover, MA 01810 USA

Epitaxy of InGaAs on GaAs with In mole fractions over 20% and layer thickness greater than 150Å is challenging due to GaAs/InGaAs lattice mismatch. Graded indium mole fraction from 0 to 53% over a thickness of 1-2 microns is a widely exploited technique for growing InGaAs on GaAs. In this technique, as the In mole fraction and the layer thickness increases, the epilayer becomes highly dislocated and relaxed. Fortunately, most of the dislocations that originate in the buffer layer bend and become parallel to the substrate and do not propagate to the surface. As the epitaxy is continued, the dislocations decrease in density and eventually high quality epi is achieved (1). Metamorphic HEMT (MHEMT)

devices are based on graded buffer InGaAlAs and offer HEMT device performance comparable to InP based devices, while being grown on GaAs substrate and as such are highly suitable for volume production. Our MHEMTs have shown remarkable properties in high frequency operation. For example, a 60% In MHEMT has achieved 0.61 dB minimum noise figure with 11.8 dB of associated gain at 26 GHz, with a Ft approaching 200 GHz (2). In this paper, we report our findings on crystalline structure of MBE grown MHEMTs. We have evaluated MHEMT structures by High Resolution X-ray Diffraction (HRXRD). These samples are grown by MBE using the graded buffer technique and their InGaAs channels have In mole fractions greater than 50%. Our results indicate that in these structures, the lower InGaAlAs barrier and the channel are tilted by 0.7° and rotated by as much as 25° with respect to the substrate. 2-D scan of $\theta/2\theta$ and ϕ on MHEMT structures are used to evaluate the InGaAs channel layer in-plane rotation. The 2-D reciprocal lattice scans of these samples show that the lower InGaAlAs barrier is not completely relaxed, and has some residual strains remaining in it. However, more remarkably the InGaAs channel layer is entirely pseudomorphic with respect to the barrier and hence exhibits very high quality electrical properties, which makes the MHEMT devices significant. While the mechanism for the lattice rotation effect is not completely understood, it is clearly the result of the strain relief by dislocation formation in the epistructure during epitaxy.

Session O. Nanometer Scale Characterization

Thursday AM
June 22, 2000

Room: Lindsey Auditorium
Location: Sturm Hall

Session Chairs: Julia Hsu, Bell Laboratories, Lucent Tech., Murray Hill, NJ 07974 USA; Randy Feenstra, Carnegie Mellon University, Dept. of Phys., Pittsburgh, PA 15213 USA

8:00 AM, 01 +

Time Evolution Studies of the Surface Potential on LTG:GaAs Using Electrostatic Force Microscopy: *M. V. Baitstuta*²; N. P. Chen¹; D. B. Janes²; M. R. Melloch²; R. Reifengerger¹; Stephen W. Howell¹; ¹Purdue University, Dept. of Phys., West Lafayette, IN 47907 USA; ²Purdue University, Sch. of Elect. and Comp. Eng., West Lafayette, IN 47907 USA

It is well known that stoichiometric n-GaAs oxidizes rapidly, within a matter of minutes, when exposed to ambient conditions. This oxide layer can play a significant role in the electrical properties of contact structures and Schottky barriers, making device construction on GaAs difficult. Low temperature grown GaAs (LTG:GaAs) has been observed to oxidize more slowly, with a time constants that appear to be hours [1]. Midgap states have been observed after 20 minutes of air exposure, indicating electrical activity [2]. These studies, along with demonstrations of low-resistance nonalloyed contacts using LTG:GaAs surface layers [3], indicate that the surface electrical properties of LTG:GaAs are well controlled even following air exposure of 20-60 minutes. One key issue regarding the electrical properties of structures utilizing LTG:GaAs is the surface electrostatic potential. Holden, et al. inferred the surface potential from near-surface electric field measurements following prolonged air exposure [4]. In typical device fabrication procedures, the oxide is chemically stripped shortly before the metal (contact or Schottky) is deposited. LTG:GaAs may play a vital role in the development of nano-scale devices, such as a linked cluster array networks. Other experiments have shown, that nano-scale ohmic contacts can be formed by nanometer sized gold clusters tethered to a LTG:GaAs substrate by xylyl dithiol [5]. It is therefore necessary to determine how the surface electrical properties evolve over the time interval following removal and formation of the surface oxide layer. In this study, we have observed the evolution of the electrostatic potential of the LTG:GaAs layer during

oxide formation on the surface. This time-evolution study was conducted using an electrostatic force microscope [6]. Utilizing standard scanning force microscopy technology allowed us to probe the surface potential with a lateral resolution ranging from 100 nanometer to 15 micrometers. The samples consisted of 100 nm thick layers of LTG:GaAs grown by MBE on a GaAs(100) substrate. Both Be-doped and undoped LTG:GaAs (both n-type) were used during this study. Millimeter sized gold reference electrodes were evaporated over a region of LTG:GaAs. The oxide layer on the LTG:GaAs was then stripped using a HCl etch. A heavily doped silicon atomic force microscope (AFM) tip was placed over the reference electrode and then over the LTG:GaAs. Sample to tip separation was held fixed by using a non-contact AFM feedback loop. The surface potential of the sample was determined by varying the voltage on the tip until the electrostatic component of the force was eliminated. The electrostatic surface potential measurements were repeated over the gold and the LTG:GaAs for several hours. As the oxide layer reformed on the LTG:GaAs, the electrostatic surface potential was observed to vary in time dramatically. Initial measurements have showed that the electrostatic surface potential increased by approximately 600 mV during a three hour period after the etch. However, observations made a few days later, showed that the electrostatic surface potential had returned near it's starting value (before the etch). [1] T. B. Ng, et al. Appl. Phys. Lett. 69, 3551 (1996). [2] Hong, et al. Appl. Phys. Lett. 68, 2258 (1996). [3] M. P. Patkar, et al. Appl. Phys. Lett. 66(11), 1412 (1995). [4] Holden, et al. Phys. Rev. B, 7795 (1998). [5] T. Lee, et al. Appl. Phys. Lett. 74, 2869 (1999). [6] M. Nonnenmacher, et al. Appl. Phys. Lett. 58, 2921 (1991).

8:20 AM, 02 +

Structural and Electronic Properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ Heterojunction Bipolar Transistors Characterized Using Cross-Sectional Scanning Force Microscopy: P. A. Rosenthal¹; E. T. Yu¹; P. J. Zampardi²; ¹University of California-San Diego, Depts. of Elect. and Comp. Eng., Mail Code 0418, 9500 Gilman Dr., La Jolla, CA 92093-0407 USA; ²IBM, Microelect. Div., 1000 River Rd., M/S 861A Essex Junction, VT 05452 USA

Accurate determination at or near the nanometer scale of layer thickness, chemical composition, and dopant distributions in semiconductor heterostructure materials is crucial for analysis and optimization of advanced device structures. Scanning probe techniques offer unique and powerful capabilities in this regard. In this work, we have used cross-sectional scanning force microscopy performed on cleaved samples in an ambient environment to measure quantitatively nanometer-scale differences in base-layer thickness and to assess dopant distributions in AlGaAs/GaAs heterojunction bipolar transistor structures. Based on local variations in electronic structure, differences in base-layer thickness between samples can be measured with accuracy better than 10nm, and variations in dopant concentration of a factor of two are readily detected. The technique employed entails the application of a bias voltage with components at dc and frequency ω between an electrically conductive probe tip and grounded sample surface. Specifically, we have used a variation of the standard EFM technique, referred to as capacitive force imaging, in which the amplitude of the scanning probe tip is detected as it oscillates in response to the electrostatic force component at frequency 2ω . We have performed a detailed analysis of the contrast mechanisms in this mode of operation and find that the amplitude contrast is dependent on the bias voltage and the local dopant concentration through the dependence of the depletion layer depth below the sample surface on these quantities. Our studies also provide an approximate measure of the charge concentration on the cleaved cross-sectional surface, which we find to be of order $\sim 4 \times 10^{-8}$ coulombs/cm², corresponding to a charged surface state density of $\sim 3 \times 10^{11}$ cm⁻². We have used capacitive force imaging to characterize the structural and electronic properties of cleaved cross-sections of $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ epitaxial layer heterojunction bipolar transistor (HBT) structures, one with 50 nm base width and the other with 120 nm base width. The contrast observed allows us to clearly delineate the emitter, base, collector, and subcollector regions within the device structure, and to distinguish regions within the collector differing in dopant concentration by a factor of two (N_D varies between 3 and 6×10^{16} cm⁻³). We have also distinguished clearly between the base widths in these samples and have precisely measured the difference to be 63 ± 3 nm, in excellent agreement with the nominal difference of 70 ± 7 nm. These results demonstrate clearly the ability, using the capacitive force imaging technique, to obtain a reliable and precise measure of differences in de-

vice dimensions between samples with accuracy better than 10nm, and to detect relatively small differences in dopant concentration, based upon the direct measurement of electronic properties. Furthermore, the demonstration of these capabilities in ambient air in a cross-sectional geometry implies the applicability of these techniques to realistic device structures with modest sample preparation requirements.

8:40 AM, 03

Observation of Coulomb Blockade and Single Electron Charging by Scanning Tunneling Spectroscopy in Artificially Patterned, Nanometer-Scale InAs Quantum Dots at 4.2K: Philip Chang¹; Chia-Hung Yang¹; Ming-Jey Yang²; ¹University of Maryland, Elect. and Comp. Eng. Depts., College Park, MD 20742 USA; ²Naval Research Laboratory, Washington, DC 20375 USA

Three-dimensional quantization of electron's kinetic energy is experimentally realized by confining electrons in a quasi-zero-dimensional quantum dot. As a result, the few electron system in a quantum dot show unique properties that could not be observed otherwise. With a tight control over the fabrication process, and thus the knowledge of the shape and geometry of the "artificial atom," one can in principle directly solve the Schrodinger equation for the ground states, and compare the theoretical simulation with experimentally observed energy spectrum. We report our recent finding of tunneling spectroscopy in individual InAs quantum dots. The sample has a double-barrier resonant tunneling structure grown by molecular beam epitaxy. A typical structure has a thick n-type InAs buffer. The 3nm/8nm/3nm AlSb/InAs/AlSb resonant tunneling structure is grown next, with a 15nm InAs capping layer on top. By using electron-beam lithography, quantum dot patterns are written on a bilayer resist (200nm PMMA on top of 500nm PMAA). With metal evaporation and lift-off, nickel (50nm in thickness and 70nm in diameter) discs are defined as etch masks in the subsequent reactive ion etching (RIE) process. The low-power, methane-based, anisotropic RIE process is specifically developed for etching away the semiconductor and stop at the bottom AlSb tunneling barrier. The InAs quantum well underneath the nickel disc is laterally confined by the abrupt, square potential and form a quasi-zero-dimensional quantum dot. This lateral confining potential is originated from the pinned surface Fermi level at the exposed InAs surface. A low-temperature (4.2K) scanning tunneling microscope (STM) is used to perform characterization. First, from topographic imaging, an individual dot is located. The tunneling tip is then driven to be in direct contact with the nickel on top of a particular quantum dot for spectroscopy. Features in the current-voltage relation owing to Coulomb blockade, Coulomb staircase can be clearly identified. Using only one quantum dot, we can observe two qualitatively different cases of I-V curves. The data can be well explained by a two-tunnel junction picture, where the fractional residual charge on the InAs quantum dot is varied without an external electrode. Compared with observations using GaAs-based heterojunctions (Ashoori et al., Physica B 184, 378-384, 1993; and Tarucha et al., Jpn. J. Appl. Phys. 36, 3918-3923, 1997), where the lateral confining potential is necessarily smooth and wide (~1micron), our approach has the advantage of (1) smallness; and (2) further increasing the lateral quantization energy by a factor of 10. Lithography patterned, RIE defined quantum dots can be more easily applied in circuits than, e.g., self-assembled InAs quantum dots (Banin et al., Nature 400, 542-544, 1999).

9:00 AM, 04

Scanning Tunneling Spectroscopy Characterization of GaAs Surfaces Passivated by MBE-Grown Ultrathin Si Layers: Seiya Kasai¹; Noboru Negoro¹; Hideki Hasegawa¹; ¹Hokkaido University, Rsch. Ctr. for Interface Quant. Elect. (RCIQE) and Grad. Sch. of Electronics and Info. Eng., North 13 West 8 Kitaku, Sapporo 060-8628 Japan

Recent trends toward nanofabrication in GaAs-based high frequency, optoelectronic and quantum devices enhance the importance of surface passivation. However, in spite of the revived interests in compound semiconductor oxides, particularly, with those by high temperature steam oxidation, the well-known problem of the surface Fermi level pinning still seems to remain, and causes serious problems in nano-scale devices. Our group proposed an approach of inserting an MBE-grown ultrathin silicon interface control layer (Si ICL) between the III-V material and the silicon-based passivating insulator such as SiO₂ and Si₃N₄. Macroscopically, this approach has led to dramatic reduction in surface state densities and enhancement surface photoluminescence properties. The pur-

pose of this paper is to characterize GaAs surfaces passivated by Si ICL in nanometer scale by scanning tunneling microscopy (STM) and spectroscopy (STS). The experiments were performed in a totally ultra-high vacuum (UHV)-based growth/processing/characterization system. The initial (001) GaAs surfaces having (2x4) and c(4x4) surface reconstructions were prepared by a conventional MBE method. The ultrathin Si layers were also formed on the GaAs surfaces by MBE. The samples were characterized in the UHV-STM chamber, the X-ray photoelectron spectroscopy (XPS) chamber and the UHV contactless capacitance-voltage (C-V) chamber. STS measurements on initial and Si ICL covered surfaces showed both normal and anomalous spectra even on the same sample surface. The anomalous spectrum was explained by a new model which includes a semiconductor band bending caused by tip-induced local charging of the surface states. A detailed 3D potential simulation confirmed that tip-induced charging of surface states produces large apparent band gap in the STS spectrum. The local surface Fermi level position (E_{FS}) was evaluated from normal STS spectra. The ultrathin Si layer was found to be transparent to STS spectra, as expected. The E_{FS} in initial GaAs surfaces was located at 1.0 eV from the conduction band edge, E_C . After formation 3/8 ML Si on c(4x4) GaAs surface, E_{FS} shifted 0.3 eV toward E_C , indicating reduction of Fermi level pinning. This result is in good agreement with XPS band-bending and UHV contactless C-V measurements. The STM images with large positive sample bias showed dark areas of a few ten nanometer size, indicating presence of pinning areas rather than isolated pinning centers with discrete levels. The ratio of finding normal STS spectra on GaAs surfaces counted by taking 400 STS spectra was found to increase dramatically from 19% to 67% by forming 3/8 ML Si on c(4x4)-(001) GaAs surface. A strong correlation was seen between the ratio and the shift of E_{FS} . Thus, Si ICL is very effective also microscopically in reducing the number and state density of pinning areas on GaAs surfaces.

9:20 AM, 05 +

Atomic Force Microscope Measurements of Molecular Layer Electrical Characteristics: *Lili Jia*¹; Jonathan A. Nichols¹; Thomas N. Jackson¹; ¹The Pennsylvania State University, Dept. of Elect. Eng., 121 Electrical Engineering East, University Park, PA 16802 USA

Self-assembled monolayers on a variety of surfaces have been extensively studied. Recently, molecular layers with potential for use as memory elements or in other molecular devices have been demonstrated [1]. However, the nanoscale device processing used in the first molecular device demonstrations is complex and makes the testing of a range of molecular device candidate materials difficult and time consuming. As an alternative, we have used an atomic force microscope (AFM), operated in contact mode with a customized probe, to rapidly characterize molecular layers. Although atomic force microscopy has frequently been used to image molecular layers, it is difficult to use typical AFM tips to measure electrical characteristics because the tip force needed for reproducible electrical contact may also disrupt the molecular layer. Scanning tunneling microscopy can be used to measure molecular conductance, but is not simple to use for electrical measurements over wide current and voltage ranges. To allow simple characterization of molecular layers we have built customized probes by attaching polystyrene spheres to a commercial AFM cantilevers. The sphere-cantilever combination is then coated with a thin conductive metal film by ion beam sputtering to obtain a smooth conductive surface. The AFM with the customized cantilever is then used to apply a small and controlled force between the conductive sphere and the sample to be measured. The smooth spherical surface spreads the force over a sufficiently large area of the molecular layer that damage can be avoided. Using this approach we have been able to characterize several self-assembled molecular layers. I. M.A. Reed, D.W. Bennett, J. Chen, D.S. Grubisha, L. Jones II, A.M. Rawlett, J.M. Tour, and C. Zhou, "Prospects for Molecular-Scale Devices", IEDM Tech. Digest p. 227, 1999.

9:40 AM Break

10:20 AM, 06 +

Microcontacts to Self-Assembled Monolayers with a Conducting AFM Tip: *David J. Wold*¹; C. Daniel Frisbie¹; ¹University of Minnesota, Chem. Eng. and Mats. Sci. Depts., Amundson Hall, 421 Washington Ave. SE, Minneapolis, MN 55455 USA

The electrical properties of individual molecules and molecular assemblies are currently of heightened interest because of potential applica-

tions in molecular electronics and new opportunities for understanding charge transport in organic systems. Molecular level electrical transport studies require innovative approaches for making electrical contacts to oriented molecules. Scanning tunneling microscopy (STM) and electrochemical methods have been used for years to study transport in surface-confined molecules. Self-assembled monolayers are commonly employed for such studies as model molecular systems because they are easily immobilized at metal electrodes. Conducting probe atomic force microscopy (CP-AFM) provides an alternative approach to electrically contacting monolayer films and the formation of metal-molecule-metal junctions. In CP-AFM, a metal-coated AFM tip is placed in direct contact, under controlled load, with the material to be probed. The technique differs from STM in that the probe is positioned using normal force feedback, which decouples probe positioning from electrical measurements. Using this technique, we have shown that CP-AFM may be used to make mechanically stable electrical contact to SAMs of alkanethiols on Au. We have probed the current-voltage (I-V) characteristics of the resulting junctions as a function of the number of methylenes in the alkane chains and the load applied to the tip-sample contact. The ease of this technique and the fine control of the probe during measurements make CP-AFM a promising approach for studying transport through molecular junctions. Further studies of dependence on conjugation, functional group distributions, orientations, and molecular dimensions will also be discussed.

10:40 AM, 07 +

Formation and Characterization of Nanometer-Sized Schottky Contacts on III-V Materials by In-Situ Electrochemical Process: *Taketomo Sato*¹; Seiya Kasai¹; Hideki Hasegawa¹; ¹Hokkaido University, Rsch. Ctr. for Interface Quant. Electro. and Grad. Sch. of Electro. and Info. Eng., North 13 West 8 Kitaku, Sapporo 060-8628 Japan

In many of the quantum devices, size- and position-controlled formation of nanometer-sized Schottky gates with good potential controllability are required. The purpose of this paper is to form nanometer-sized Schottky contacts by a novel in-situ electrochemical process, and to investigate their electrical properties from theoretical and experimental viewpoints. By using electron-beam resist patterns, the electrochemical process can selectively form various metal patterns on various structures without the conventional lift-off process, since the electrochemical reaction takes place only on the conductive area. In this study, the position- and size-controlled metal nano-Schottky contacts with a diameter of 20-100 nm were successfully formed on n-GaAs and n-InP substrates using the optimized pulsed electrochemical process. The I-V characteristics of the nano-Schottky contacts were measured using an atomic force microscope (AFM) system with a conductive probe. By a systematic study, it was found that the Schottky barrier heights (SBHs) become more and more metal workfunction dependent as the dot size is reduced. An SBH value of 860 meV was obtained for Pt/n-InP which is about 400 meV larger than the conventional value. This strongly indicates remarkable reduction of the Fermi level pinning at metal-semiconductor nano-interfaces. However, it was also found that the log I-V plots showed highly non-linear characteristics with a large ideality factor (n) of 1.3-2.0. From a detailed computer simulation that the potential distribution underneath the metal contact was found to be strongly modified by the effect of an environmental Fermi level pinning at free semiconductor surface surrounding the metal contact. This modification results in formation of a saddle point potential under the forward bias and changes the effective Schottky barrier height as a function of the bias. Theoretical log I-V curves including this effect showed excellent agreements with the experimental data. Furthermore, the calculated C-V characteristics showed much smaller movements of the depletion layer with bias underneath the nano-Schottky contacts due to the environmental Fermi level pinning. These results show that the reduction of the environmental Fermi level pinning is extremely important to realize good potential control in nanometer-sized Schottky contacts.

11:00 AM, 08 +

A Physically Based Conduction Model for Ohmic Nanocontacts to GaAs Utilizing Low-Temperature-Grown GaAs: *Nien-Po Chen*¹; Takhee Lee¹; D. B. Janes²; R. Reifenger¹; J. M. Woodall³; M. R. Melloch²; ¹Purdue University, Dept. of Phys., 1396 Physics Bldg., West Lafayette, IN 47907 USA; ²Purdue University, Sch. of Elect. and Comp. Eng., 1285 Electrical Engineering Bldg., West Lafayette, IN 47907 USA; ³Yale University, Dept. of Elect. Eng., New Haven, CT 06520 USA

As device dimensions shrink into the nanometer scale, the realization of low-resistance ohmic contacts at the nano scale becomes increasingly important. Nano-scale non-alloyed ohmic contacts to n-GaAs have been reported utilizing gold clusters, xylyl dithiol (XYL), and low-temperature-grown GaAs (LTG:GaAs) [1]. A specific contact resistance of $1 \times 10^{-7} \Omega \text{ cm}^2$ has been achieved, comparable to the best contacts to date for micron-scale GaAs ohmic contacts. It has been observed that samples with a Be-doped LTG:GaAs cap layer perform better than those with an undoped LTG:GaAs layer. This finding is somewhat counterintuitive, since Be is an acceptor and the conductive layer is n-type. It is important to understand this behavior, as well as the role of defect states in LTG:GaAs in the electron transport. In order to understand the performance of this nanocontact structure and to provide guidance for development of nano-scale contacts to other materials, we have developed a conduction model for the contact structure, based on our previous modeling work on micron-scale non-alloyed ohmic contacts. Our model describes the broad defect band in LTG:GaAs layer with As antisites and Ga vacancies, based on various experimental observations by others. The calculated Fermi level in the bulk LTG:GaAs by the model, as well as calculated surface electric field, are consistent with various independent experiments [2, 3]. The nanocontact structure is modeled as a metal-insulator-semiconductor (MIS) structure. By simulating XYL as an wide-energy-gap insulator and using a proper description of the defect states in LTG:GaAs, the energy band profile can be easily calculated by a Poisson equation solver. The preliminary results show that the structure with an undoped LTG:GaAs cap layer has no defect states participating the transport, but purely electron tunneling through the energy barrier. On the other hand, the structure with a Be-doped LTG:GaAs cap layer has significant defect states around the Fermi level, allowing electrons to travel through mid-gap band of states, followed by tunneling from the defect band to the n-GaAs. The mechanisms of improved contact resistance via Be doping will be discussed. References: [1] T. Lee et al., Appl. Phys. Lett. 76, pp. 212 (2000); [2] R. M. Feenstra et al., Phys. Rev. Lett. 71, pp.1176 (1993); [3] T. Holden et al., Phys. Rev. B 58, pp.7795 (1998).

11:20 AM, 09 Late News

11:40 AM, 010 Late News

Session P. Transport Properties in Nitride Structures

Thursday AM Room: Sturm Auditorium
June 22, 2000 Location: Sturm Hall

Session Chairs: Joan Redwing, Penn State University, Matls. Sci. and Eng. Dept., University Park, PA 16802 USA; Wladek Walukiewicz, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA

8:00 AM, P1

Low-Temperature Electron Transport in the AlGaIn/GaN/AlGaIn Double Heterostructures: Yulia P. Smorchkova¹; R. Vetry¹; R. Coffie¹; D. S. Green¹; J. S. Speck¹; U. K. Mishra¹; ¹University of California, Elect. and Comp. Engineering Depts., Santa Barbara, CA 93106 USA

We report on the low-temperature electron transport properties of unintentionally-doped AlGaIn/GaN/AlGaIn double heterostructures (DHS) grown by plasma-assisted molecular beam epitaxy. The Hall measurements show that the density of the polarization-induced two-dimensional electron gas (2DEG) is lower in the DHS in comparison to single heterostructures. The decrease can be associated with the strong built-in electric field in the GaN quantum well (QW) region. The variation of the low-temperature electron mobility with GaN QW width is consistent with the earlier experiments on the single AlGaIn/GaN heterostructures which identified interface roughness as the dominant scattering mechanism. In the wide GaN quantum wells ($d > 10 \text{ nm}$) polarization-enhanced electron confinement at one of the AlGaIn/GaN heterointerfaces allows

2D electrons not to be affected by the second heterointerface to a large extent. Therefore the dependence of the low-temperature electron mobility on the 2DEG density in the wide GaN quantum well structures is similar to the one in the single heterostructures. However, in the thin quantum well structures the presence of the bottom GaN/AlGaIn heterointerface leads to a decrease in the electron mobility.

8:20 AM, P2

Screening of Dislocation Scattering in High-Density 2D Electron Gas AlGaIn/GaN Heterostructures: J. W. Yang¹; M. Asif Khan¹; W. Knap²; X. Hu¹; G. Simin¹; P. Prystawko³; M. Leszczynski³; I. Grzegory³; S. Porowski³; R. Gaska⁴; M. Shur²; B. Beaumont⁵; M. Teisseire⁵; G. Neu⁵; ¹University of South Carolina, Dept. of ECE, 301 S. Main St., Rm. 3A80, Columbia, SC 29208 USA; ²Rensselaer Polytechnic Institute, Depts. of ECSE and CIEEM, Troy, NY 12180 USA; ³High Pressure Research Center UNIPRESS, Polish Acad. of Sci., Sokolowska 29/3, Warsaw PL01-142 Poland; ⁴Sensor Electronic Technology, Inc., 21 Cavalier Way, Latham, NY 12110 USA; ⁵CNRS-CRHEA, Rue Bernard Gregory, Valbonne-Sophia-Antipolis F-06560 France

We present the comparative study of a high-density 2D electron gas (2deg) in AlGaIn/GaN heterostructures grown over bulk GaN, sapphire and insulating 4H-SiC substrates under the same conditions. The results of this study are used to establish the role of threading dislocations in 2deg transport properties. The AlGaIn/GaN heterostructures were grown by low pressure MOCVD under the same conditions on high-pressure bulk GaN, insulating 4H-SiC and sapphire substrates. The 2d electron gas channel on bulk GaN substrates exhibits excellent electronic properties with room temperature electron Hall mobility as high as $\mu \sim 1650 \text{ cm}^2/\text{Vs}$ combined with a very large electron sheet density $n_s \sim 1.4 \times 10^{13} \text{ cm}^{-2}$. The highest room-temperature mobility of $1,650 \text{ cm}^2/\text{Vs}$ was measured for homo-epitaxial layers, which is about 15% higher than for the heterostructures grown on 4H-SiC. Since the estimated number of threading dislocations in the two samples differs by a factor of 10^4 to 10^6 , the observed close values of the low field mobility in the homoepitaxial and hetero-epitaxial structures confirm strong screening effects in the high density of the 2-deg. The obtained results indicate that at high sheet densities and high temperatures threading dislocations are screened and play only minor role in 2D electron transport.

8:40 AM, P3 +

Characterization of AlGaIn/GaN Lateral PIN Junctions and Schottky Rectifiers Grown by MOCVD: Bryan S. Shelton¹; Ting Gang Zhu¹; Damien J. H. Lambert¹; Michael M. Wong¹; Ho Ki Kwon¹; Uttiya Chowdhury¹; Russell D. Dupuis¹; ¹The University of Texas at Austin, Microelect. Rsch. Ctr., PRC/MER-R9900, Austin, TX 78712-1100 USA

The exploration of new techniques to improve the quality of the AlGaIn/GaN heterojunction in device structures is crucial to solving the material and processing-related problems that have hindered nitride device development thus far. Because of the insulating nature of the sapphire substrate used by most workers for GaN heteroepitaxial growth, electronic devices must be contacted entirely from the top of the device, unlike devices grown on SiC substrates. This requires etching of the device structure. Furthermore, many devices require etching to provide the definition of the device area. To overcome the problems of sidewall passivation and damage during etching, we have studied selective-area regrowth and photoelectrochemical (PEC) etching to study the leakage currents, device breakdown, and blocking voltage limitations in III-nitride materials. We have measured the electrical characteristics of AlGaIn/GaN lateral and vertical p-i-n junctions and Schottky rectifiers grown by metalorganic chemical vapor deposition (MOCVD). The device structures are grown in an EMCORE D125 UTM MOCVD system at pressures of $\sim 100 \text{ Torr}$ and temperatures in the range $1030^\circ\text{C} < T_g < 1100^\circ\text{C}$. Hydrogen is main process gas and carrier gas for the metal alkyls. Ammonia is used as the N source and adduct-purified trimethylgallium (TMGa) and trimethylaluminum (TMAI) are used as Column III precursors, with a V/III ratio of $\sim 2,500$ -5,000. The samples are prepared by first growing various device layers on (0001) sapphire at 1050°C ; e.g., a $2\mu\text{m}$ layer of n-type GaN with an optional thin $30\text{nm Al}_x\text{Ga}_{1-x}\text{N}$ layer for the P-N rectifier or $\sim 2\mu\text{m}$ of n+ GaN with $\sim 2\mu\text{m}$ of undoped GaN. Next, the selective-regrowth regions are defined using a $\sim 100\text{nm}$ thick SiO_2 mask deposited by plasma-enhanced chemical vapor deposition using SiH_4 and N_2O precursors. Conventional optical lithography and wet chemical etch-

ing are used to produce the device patterns in the SiO₂ mask layer. The samples are patterned with Ti/Pt using conventional liftoff techniques. Photoelectrochemical etching using KOH solutions is employed to etch through the undoped layer to produce recessed regions into which the p- and n-type device regions will be grown for the lateral devices. Vertical devices are made using reactive-ion etching and PEC for comparison of the device leakage. The leakage current vs. breakdown voltage for a variety of lateral and vertical AlGaN/GaN devices processed using RIE and PEC etching have been measured. Lateral PIN and P-HFET-N devices show leakage currents related to surface effects. On-resistances below 50 mΩ-cm² and blocking voltages in excess of -100V are observed for 40μm-dia. vertical-geometry GaN Schottky rectifiers with relatively thin "i" regions of ~2μm. Comparison between different growth conditions and processing techniques will be presented and their effect on device performance will be described.

9:00 AM, P4 +

Comparison of Charge Trapping Effects in AlGaN/GaN Heterostructures Based on Al Composition, Doping and Growth Technique: *Kurt V. Smith*¹; X. Z. Dang¹; E. T. Yu¹; J. M. Redwing²; D. A. Keogh²; C. Elsass³; B. Heying³; J. Speck³; ¹University of California-San Diego, Elect. and Comp. Eng. Depts., 9500 Gilman Dr. 0407, La Jolla, CA 92093 USA; ²ATMI/Epitronics; ³University of California-Santa Barbara, Santa Barbara, CA USA

The design and optimization of nitride heterostructure devices requires, to an ever increasing degree, detailed characterization and understanding of defects, structural inhomogeneities, and the associated local variations in electronic structure to which they give rise. We have used scanning capacitance microscopy (SCM) and atomic force microscopy (AFM) to compare the local surface structure and electronic properties of Al_xGa_{1-x}N/GaN heterostructure field effect transistor (HFET) epitaxial layer structures grown by both metal organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). The epitaxial layers were grown on either 4H-SiC or sapphire and consisted of a thick relaxed GaN layer capped with a thin (nominally 20-30nm) strained Al_xGa_{1-x}N layer with Al compositions varying from 10% to 26%. Both doped and undoped Al_xGa_{1-x}N barrier layer structures have been investigated. Our studies using SCM have demonstrated that the application of a DC bias voltage of ~6V or greater in magnitude between an Al_xGa_{1-x}N/GaN HFET sample structure and a conducting proximal probe tip induces localized charge trapping at various depths within the sample volume below and in the immediate vicinity of the probe tip. By inducing charge trapping in highly localized regions and subsequently obtaining SCM images of charged and adjacent uncharged regions, information concerning the presence, lateral and vertical distribution, and lifetime of trapped charge may be obtained. Acquisition and analysis of scanning capacitance data as a function of applied bias voltage allows information pertaining to both the lateral and vertical distribution of trapped charge to be obtained with submicron to nanometer-scale resolution. In all cases, exposure of samples to ultraviolet light is found to remove all indication in SCM images of trapped charge in these samples. SCM studies of a broad range of sample structures show that such charge trapping effects occur in samples grown by both MBE and MOCVD, for both nominally undoped and intentionally doped samples, and over the entire range of Al compositions studied. In MOCVD-grown Al_xGa_{1-x}N/GaN HFET samples, a combination of bias-dependent SCM imaging and numerical simulation of capacitance properties indicates that positive trapped charge is present at the surface, negative trapped charge at or near the Al_xGa_{1-x}N/GaN interface, and positive trapped charge in the GaN layer. Significant variations in topography and SCM contrast are observed in comparisons of intentionally doped and nominally undoped samples, suggesting that doping within the Al_xGa_{1-x}N layer significantly alters both surface morphology during growth and local electronic structure at the nanometer to micron scale. Finally, local charging and SCM imaging of MBE-grown Al_{0.1}Ga_{0.9}N/GaN HFET structures indicates that the time required for dissipation of trapped charge is significantly shorter in these structures than in MOCVD-grown structures with Al_xGa_{1-x}N compositions ranging from 0.15 to 0.26.

9:20 AM, P5

Recombination Generation Noise and Surface States in AlGaN/GaN-Based Field Effect Transistors: *Sergei Rumyantsev*¹; Mikhail Levinshstein²; Nezhil Pala¹; Michael S. Shur¹; R. Gaska²; A. Khan³; S. Simin³; J. Yang³; ¹Rensselaer Polytechnic Institute, CIEEM, c/o M. S. Shur, CII-9017, Troy, NY 12180 USA; ²Sensor Electronic Technology, Inc., 21

Cavalier Way, Latham, NY 12110; ³University of South Carolina, Columbia, SC 29208 USA

We report on the temperature studies of low frequency noise in AlGaN/GaN and AlGaN/GaN HFETs and MOS-HFETs for devices with a relatively low level of noise. In these devices, one could distinguish the contribution from the generation-recombination noise superimposed on 1/f noise in the frequency range from approximately 100 to 2,500 Hz. Previously, we related such a noise to a trap level with activation energy close to 0.4 eV. On these new samples, the generation-recombination noise is linked to the surface state with a much larger activation energy (0.8 to 1 eV). The temperature dependence of the measured noise spectral density has a pronounced maximum. The inverse temperature corresponding to the position of the maximum is a linear function of the log of frequency. This dependence is typical for the generation-recombination noise. The activation energy extracted from these Arrhenius plots is 0.8 eV to 1 eV for different devices on the same wafer. The spectral density corresponding to the maximum in the temperature dependence is inversely proportional to frequency. A very large activation energy indicates that this noise is probably related to the surface or interface state in these devices. We develop a model describing the generation-recombination noise in case when it is caused by the surface state at the metal/barrier interface. The model assumes that the Fermi level is pinned at this surface state. This theory allows us to estimate the concentration, electron capture cross of the surface states, and the energy position relative to the conduction band) responsible for this noise (on the order of 5x10¹² cm⁻³). These results show that the quality of the metal-semiconductor is crucial for the low frequency noise reduction.

9:40 AM Break

10:20 AM, P6

Properties of the Channel Layer in GaN MODFETs Grown on Insulating C-doped GaN Template Layers by Reactive (Ammonia-) MBE: *H. Tang*¹; J. B. Webb¹; J. A. Bardwell¹; S. Raymond¹; S. Moisa¹; S. Rolfe¹; ¹National Research Council, Institut. for Microstruct. Sci., Montreal Rd., M-50, Rm. 254, Ottawa, Ontario K1A 0R6 Canada

We demonstrated recently the growth of high mobility GaN/AlGaN MODFET structures on insulating C-doped GaN template layers by ammonia-MBE [1]. The newly developed carbon doping technique has enhanced the reliability and reproducibility of the device structures by ensuring device isolation through controlled doping. The AlGaN/GaN interface, however, should not be formed directly on the C-doped GaN layer since the latter contains a large concentration of compensation centers as well as crystalline defects. By growing a channel layer (a 2000-4000 Å thick undoped GaN layer) between the C-doped template layer and the AlGaN barrier layer, we observed in the structures grown high quality 2DEG characterized by room temperature mobilities >1000 cm²/Vs and well resolved Shubnikov-de Haas oscillations. It is remarkable that a drastic increase of purity and crystalline quality would occur during the growth of such a thin channel layer. In the present work, the bulk properties of the channel layer itself have been studied on specifically grown samples with structures consisting of only the C-doped template layer and a 4000 Å thick channel layer. The channel layers were doped with Si to different concentrations. The samples were studied using Hall-effect measurements, PL, X-ray diffraction, AFM, and TEM. The Si-doped channel layers exhibited remarkably high bulk mobilities of 490, 386, and 191 cm²/Vs with carrier concentrations of 8.0x10¹⁶, 5.3x10¹⁷, and 2.86x10¹⁸/cm³, respectively. Theoretical fitting of the transport measurement data taking into account the effect of dislocation scattering finds a quite low density (7x10⁸/cm²) of threading dislocations. TEM pictures show that most threading dislocations terminate within the C-doped layer, and the channel region is remarkably clean from defects. The C-doped GaN template layers show quite broad X-ray DC rocking curves with FWHM values of 500-600 arcsec. The PL of the C-doped layers is dominated by the yellow luminescence. These characteristics indicate that large concentrations of non-radiative centers as well as other defects have been introduced into the films due to carbon doping and possibly ion damage from the ionic doping source. In contrast, the PL of the channel layers shows intense excitonic emissions and very weak yellow luminescence. SIMS analysis reveal abrupt change of doping at the C-doped template layer/Si-doped channel layer interface. The quite abrupt change of crystalline quality of the thin channel layer with

regard to the thick C-doped base layer is probably caused by an abrupt change of static strain across the two differently doped layers.

10:40 AM, P7 +

Role of Barrier and Buffer Layer Defect States in AlGaIn/GaN 2DEG HEMT Structures: *Shawn T. Bradley*¹; Alexander P. Young²; Leonard J. Brillson²; M. J. Murphy³; William J. Schaff³; ¹Ohio State University, Dept. of Phys., 2015 Neil Ave., 205 Dreese Lab., Columbus, OH 43210 USA; ²Ohio State University, Dept. of Elect. Eng., 2015 Neil Ave., 205 Dreese Lab., Columbus, OH 43210 USA; ³Cornell University, Dept. of Elect. Eng., Ithaca, NY 14853 USA

We have used low energy electron-excited nanoscale luminescence spectroscopy (LEENS) to detect the defects in each layer of AlGaIn/GaN HEMT device structures and to correlate their effect on 2DEG confinement. We investigated six high-quality AlGaIn/GaN heterostructures of varying electrical properties using incident electron beam energies of 0.5-20 keV to probe electronic state transitions within each of the heterostructure layers. Heterostructures of nominal 30% Al concentration grown on GaN buffer layers on sapphire substrates by plasma-assisted molecular beam epitaxy exhibited polarization-induced electron densities of $\sim 1 \times 10^{13} \text{ cm}^{-2}$ with room temperature mobilities ranging from 570-1480 cm^2/Vs . Whereas capacitance techniques sense changes in state populations near the edge of the depletion width, the extremely high depth selectivity of excitation combined with relatively short minority carrier diffusion lengths enables LEENS to depth profile electronic transitions even in films of only a few nanometers or less. In general, the spectra exhibit AlGaIn band edge emission at $\sim 3.8\text{-}3.9\text{eV}$ or $\sim 4.1\text{eV}$, GaN band edge emission at $\sim 3.4\text{eV}$, a broad yellow luminescence (YL) feature centered at $\sim 2.1\text{eV}$, a large emission in the infrared ($< 1.5\text{eV}$) from the AlGaIn layer, and a broad emission at $\sim 3.3\text{-}3.5\text{eV}$ that varies with electron beam exposure time. The LEENS depth profiles reveal differences between successful and failed structures and highlight the importance of YL in the near 2DEG region. Most of the HEMT structures showed YL emission that increased with depth toward the sapphire substrate. For a structure where no 2DEG was obtained, the YL emission was centered at a higher energy of 2.34 eV and peaked inside the AlGaIn layer. Also the GaN band edge emission appeared to shift as a function of excitation depth from of 3.28 eV near the AlGaIn/GaN interface region to 3.4eV in the GaN buffer. For comparison, Mishra, et al. [1] have noted the importance of surface donor-like states at 1.42 eV below the conduction band edge in the AlGaIn to account for the inferred band bending and the fit to the sheet carrier density. The detected AlGaIn defect emission supports the existence of such states localized within the 25 nm barrier layer. New spectral studies are underway to identify growth parameters systematically on the same wafer surface that optimize conditions for high frequency, high power performance. This work is supported by Office of Naval Research grants No. N00014-00-1-0042 (Dr. Colin Wood), No. N00014-96-1-1223, and No. N00014-95-1-0926 (Dr. John Zolper.)

11:00 AM, P8

Thermal Conductivity of Fully and Partially Coalesced Lateral Epitaxial Overgrown GaN/Sapphire (0001) Using a Scanning Thermal Microscope: *D. I. Florescu*¹; V. M. Asnin¹; Fred H. Pollak¹; A. M. Jones²; J. C. Ramer²; M. J. Schurman²; I. Ferguson²; ¹Brooklyn College of CUNY, Phys. Dept. and NY State Ctr. for Adv. Tech. in Ultrafast Photo. Matls. and Appls., Brooklyn, NY 11210 USA; ²EMCORE Corporation, Somerset, NJ 08873 USA

We have measured high spatial resolution thermal conductivity (k) at 300K of both fully- and partially-coalesced (different patterned sectors) GaN/sapphire (0001) samples, fabricated by lateral epitaxial overgrowth (LEO) using a ThermoMicroscope's scanning thermal microscope (SThM). We were able to place the SThM tip and view its position on the sample to within $\sim 1 \text{ nm}$. On the partially-coalesced samples AFM imaging was performed in order to correlate the SThM results with the details of the overgrowth patterning. An ensemble of a SiN_x mask layer with 4 mm wide stripes separated by 2 mm and 16 mm pitches placed on top of a 2 mm thick, undoped GaN base layer was used to promote LEO. Fully-coalesced GaN was obtained for the 2 mm stripe separation. On the fully-coalesced sample we found $1.86 \text{ W/cm-K} < k < 2.05 \text{ W/cm-K}$ over a distance of approximately 50 mm. The partially-coalesced sample had $2.00 \text{ W/cm-K} < k < 2.10 \text{ W/cm-K}$ on the overgrown regions, which were determined by AFM imaging. These latter values are higher than $k \sim 1.95$

W/cm-K on hydride vapor phase epitaxy (HVPE) material, $k \sim 1.7\text{-}1.8 \text{ W/cm-K}$ on LEO material using SThM [2], $k \sim 1.55 \text{ W/cm-K}$ on LEO samples using a third-harmonic technique, and $k \sim 1.3 \text{ W/cm-K}$ on a thick HVPE sample. A theoretical estimate of 1.7 W/cm-K was deduced by Slack. The implications of these results for device applications in the area of opto-electronics and high power electronics will be discussed.

11:20 AM, P9 +

The Temperature Dependence of Thermal Conductivity of GaN Materials: *Chongyang Luo*¹; Hugues Marchand²; D. R. Clarke¹; S. P. DenBaars¹; ¹University of California, Coll. of Eng., Santa Barbara, CA 93106 USA; ²University of California, Matls. and ECE Depts., Santa Barbara, CA 93106 USA

The thermal conductivity of MOCVD-LEO GaN and HVPE GaN films grown on sapphire substrates have been measured from 320K down to 40K using an electrical third-harmonic technique. The values of the thermal conductivity and their temperature dependence are substantially larger than the original data for GaN presented by Sichel and Pankove. In contrast to Sichel and Pankove's data, in which thermal conductivity reached a peak at around 200K, our results indicate that the thermal conductivity continues to rise as the temperature is decreased until reaching a maximum value that is correlated with the crystalline quality of the films. At all temperatures investigated, the LEO GaN has the highest thermal conductivity, followed by our HVPE GaN and then the commercial HVPE GaN. The peak values for these three films were approximately 80K, 100K and 120K, respectively. The corresponding thermal conductivities were 946, 444, and 324 W/mK for the LEO, UCSB and commercially grown films, respectively. (These low temperature values are lower bound values for reasons that will be described). The thermal conductivity at room temperature for the same three films are 161, 130 and 120 W/mK, respectively. The thermal conductivities and the relative values of the different films are consistent with the measured thermal conductivity being limited by extrinsic effects. The nature of the possible limiting defects is the subject of continuing characterization on a variety of GaN films but the relative thermal conductivities of the three films is related to their dislocation density: $\sim 10^6 \text{ cm}^{-2}$ for the LEO GaN, $\sim 10^8 \text{ cm}^{-2}$ for our HVPE film and a higher density for the commercial HVPE material. Finally, it is emphasized that the thermal conductivity values that we measure using the electrical third-harmonic method are the average over the volume of material probed by the thermal waves. For our particular electrode arrangement, this is over a semi-cylindrical volume 700 microns long and tens of microns radius. (As the measurements are made over a range of frequency, 100-10kHz, the effective radius also varies). Higher local values, as reported by Asnin et al using an AFM-based technique, could undoubtedly exist from place to place. This work was supported by the Office of Naval Research under MURI grant no. N00014-98-10654.

11:40 AM, P10 +

Structural Characterization of GaN/AlGaIn Heterojunctions Grown by MBE: *Sangbeom Kang*¹; W. Alan Doolittle¹; Stuart R. Stock²; April S. Brown¹; Z. R. Dai²; Z. L. Wang²; ¹Georgia Institute of Technology, Sch. of Elect. and Comp. Eng., MiRC, 791 Atlantic Dr., Atlanta, GA 30332-0269 USA; ²Georgia Institute of Technology, Sch. of Matl. Sci. and Eng., Bunger Henry Bldg., 778 Atlantic Dr., Atlanta, GA 30332-0245 USA

LiGaO_2 (LGO) offers promise as an alternative and attractive substrate for GaN growth due to its relatively small lattice mismatch, and the fact that growth polarity is easily controlled by the choice of the substrate termination. In this study, we present structural data (high resolution TEM and X-ray diffraction) and surface morphology data (AFM) for GaN and AlGaIn on LGO, with comparisons to growth on sapphire and HVPE GaN/sapphire. MBE growth with an rf-plasma nitrogen source was used to produce the films. A key factor in the development of LGO substrates has been the quality of the surface polish-typically as-received substrates have scratches, pits, and a typical range of rms surface roughness of 4 -15 nm. We have developed an improved polish to realize improved substrate surface quality. Typical values of rms roughness for our polished substrates are 0.5-5 nm. In order to achieve high quality GaN on LGO we utilize; 1) Smooth polished substrates with rms roughness of less than 1.5nm; 2) Ga-rich growth conditions at 650-700°C substrate temperature; and 3) cation-terminated substrate to nucleate a Ga-terminated epitaxial layer. Typical dislocation densities are mid- 10^8 cm^{-2} on

LGO with localized regions of in the low 10^7 cm^{-2} range. Using high resolution TEM, we make two critical observations for GaN growth on LGO. First, we observe that the GaN-LGO interface exhibits a high degree of perfection with no disorder resulting from defective buffers found with other substrates. This is consistent with the observation of a (2x2) RHEED pattern with well-defined streaks at the initiation of growth. In addition, we have examined the AlGaIn-GaN interface. At this interface, we observe both bilayer and monolayer steps and atomically smooth regions of at minimum, 100's nm in extent. Bilayer steps may result from anisotropic step flow growth in wurzite crystal structure. These steps may be an important factor in optimizing electron mobility in heterojunction FET structures. We observe step-flow growth for $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ at a temperature of 650°C directly on an MBE grown GaN buffer on LGO. Clear steps and terraces are observed and are primarily linear. However, locally around dislocation cores shown as tiny pit holes in the AFM image, the growth pattern appears more typical of MBE spiral growth. Within 100nm diameter of the relatively few dislocations that exist, the growth mode appears to be dislocation-mediated resulting in extruded features. The dislocation density estimated from the AFM image is $5 \times 10^8 \text{ cm}^{-2}$ which agrees with the result of our previous TEM analysis. Finally, we observe much improved surface morphology, as characterized by grain size and surface smoothness for growth of AlGaIn on LGO in comparison to HVPE GaN templates on sapphire and direct growth on sapphire. The double crystal x-ray diffraction curves of AlGaIn on LGO show the lowest FWHM values for both symmetric $\langle 00.4 \rangle$ and asymmetric $\langle 10.5 \rangle$ reflections (243 arcsec and 397 arcsec, respectively), compared to AlGaIn on HVPE GaN (478 arcsec and 503arcsec, respectively), and AlGaIn on sapphire (449 arcsec and 850 arcsec, respectively).

Session Q. SiC Contacts and Ion Implantation

Thursday AM Room: Driscoll Center
 June 22, 2000 North - Pub

Session Chairs: Marek Skowronski, Carnegie Mellon University, Dept. of Matls. Sci., Pittsburgh, PA 15213 USA; Mike Capano, Purdue University, West Lafayette, IN 47907 USA

8:00 AM, Q1 +

Schottky Barrier Height Dependence on the Metal Work Function for p-type 4H-Silicon Carbide: *Sang-Kwon Lee*¹; Carl-Mikael Zetterling¹; Mikael Ostling¹; ¹KTH Royal Institute of Technology, Dept. of Elect., Electrum 229, Kista S-164 40 Sweden

Recently, Itoh et. al. reported the Schottky barrier height of several metals to n-type 4H-SiC. They suggest that the barrier height depends on the metal work function without evidence of strong Fermi-level pinning, and with a linear relationship with slopes of 0.7 for Si-face of n-type 4H-SiC. Complementary studies on p-type 4H-SiC are required to investigate Fermi-level pinning and the Schottky-Mott Model. In this work, we investigated Schottky barrier diodes of several metals (Ti, Ni, and Au) having different metal work functions to p-type 4H-SiC (Si-face) using I-V and C-V characteristics. The Schottky diodes were fabricated by e-beam evaporation. Diodes were patterned by photo-lithography and etched using $\text{H}_2\text{O}_2+\text{NH}_3$, $\text{HCL}+\text{CH}_3\text{COOH}+\text{H}_2\text{NO}_3$, and $\text{KI}+\text{I}_2+\text{H}_2\text{O}$ for Ti, Ni and Au, respectively. Annealed Ni and Al were employed as backside Ohmic contacts. Ti, Ni, and Au contacts showed excellent Schottky behaviors with stable ideality factors of 1.07, 1.23, and 1.06 for Ti, Ni, and Au, respectively in the range of 25°C to 300°C. The Schottky barrier height (SBH) was 1.96, 1.41, and 1.42 eV for Ti, Ni, and Au, respectively from I-V characteristics. The results (SBH 2.00, 1.65, and 1.45 eV for Ti, Ni, and Au, respectively) from C-V characteristics were consistent with that of I-V characteristics. Based on our measurements for p-type 4H-SiC, the SBH (ϕ_{BP}) and metal work function (ϕ_{m}) show a linear relationship of $\phi_{\text{BP}}=4.14-0.51 \phi_{\text{m}}$ and $\phi_{\text{BP}}=4.05-0.47 \phi_{\text{m}}$ for I-V and C-V characteristics,

respectively. We did not observe strong Fermi-level pinning for p-type 4H-SiC, and the SBH depends on the metal work function with slopes ($S=\phi_{\text{BP}}/\phi_{\text{m}}$) of 0.47 to 0.51. From the Schottky-Mott model, the sum of the SBH for n-type and p-type semiconductor should approximately be equal to the energy band gap of the semiconductor (in our case 3.12 eV for 4H-SiC). We found the sum of SBH to be 3.13 eV ($\phi_{\text{BN}}=1.17$, $\phi_{\text{BP}}=1.96$), 2.93 eV ($\phi_{\text{BN}}=1.62$, $\phi_{\text{BP}}=1.41$), and 3.08 eV ($\phi_{\text{BN}}=1.73$, $\phi_{\text{BP}}=1.42$) for Ti, Ni, and Au, respectively. For n-type, we used the SBH values from Itoh et. al. Our results for 4H-SiC are consistent with the temperature dependence of the energy bandgap E_g , shows no strong Fermi-level pinning, and satisfies the Schottky-Mott model.

8:20 AM, Q2

A UHV Study of Ti/SiC Schottky Barrier Formation: *Angela Kestle*¹; Steve Wilks¹; Mark Pritchard¹; Phil Mawby¹; ¹University of Wales-Swansea, Dept. of Elect. Eng., Semicond. Interfaces Lab., Singleton Park, Swansea, Wales SA2 8PP UK

The formation of high temperature Schottky diodes to 4H-SiC has received considerable attention in recent years. In particular, obtaining reproducible high quality SiC contacts using standard cleanroom processing techniques alone has proved difficult. Within this paper, we present results on the formation of Ti/SiC Schottky barriers under UHV conditions. Methods of sample preparation include both a standard RCA clean and a UHV clean by thermal desorption. An XPS study was performed to examine the chemical interactions occurring at the Ti-SiC interface for sub-monolayer Ti deposition and as a function of increasing Ti coverage. An investigation into the conversion of the contact from Schottky to ohmic, and the temperature of formation of titanium silicide, was also conducted by sequentially annealing the Ti/SiC contact from 500°C upto 1250°C. In addition, a parallel study was performed whereby a single thick (35nm) layer of Ti was deposited in-situ onto a UHV-clean SiC epilayer and patterned, using standard photolithographic techniques, to form circular diodes of diameter 650 μm . The diodes were then characterised electrically, using an I-V technique, and the barrier height and ideality factor extracted using thermionic emission theory. A Schottky barrier height of 1.2eV with an ideality, n of 1.1 was measured. Reverse voltage breakdown measurements in excess of 500V were also recorded. Based on the results of the XPS study, the implications for high temperature Ti/SiC Schottky diodes are discussed.

8:40 AM, Q3 +

Influence of Carrier Freeze-Out on SiC Schottky Junction Admittance: *Andrei V. Los*¹; Michael S. Mazzola¹; ¹Mississippi State University, Elect. and Comp. Eng. Depts., Emerging Matls. Rsch. Lab., P.O. Box 9571, Mississippi State, MS 39762-9571 USA

Measurement of semiconductor junction differential admittance constitutes the basis of several characterization techniques, such as capacitance-voltage doping profiling. This technique is based on certain assumptions, one of which is the assumption of complete doping ionization. This condition is satisfied at room temperature for most dopants in traditional narrow bandgap semiconductors, such as Si. However, in silicon carbide, which is one of the most promising semiconductor materials for high power and harsh environment applications, the energy levels of commonly used dopants are relatively deep and can be in a partial carrier freeze-out even at room temperature. For instance, nitrogen, which is the shallowest donor in SiC, has the activation energy of about 50 meV on hexagonal site in 4H-SiC. The activation energies of nitrogen on the cubic site in 4H-SiC, various nitrogen sites in 6H-SiC, and common acceptors, such as Al and B, are even larger. Therefore, in the case of SiC (and any other semiconductor with a "deep" dominant dopant), the assumption of complete ionization can lead to an error in the doping profile extracted from the capacitance-voltage data due to the possibility of impurity level charging-discharging by the measurement ac signal. Traditional theoretical treatment of the semiconductor junction admittance assumes this measurement signal to be small (with respect to kT/q), which may not be so for some typical differential admittance measurements, and can lead to erroneous interpretation of the experimental data. We develop a physical model, which allows analysis of the spectral content of Schottky junction current with an arbitrary periodic stimulation, and thus calculate the differential admittance more accurately than it can be done using the small-signal approximation based models. The model is based on quite general assumptions of an equilibrium nondegenerate free carrier concentration, a negligible minority carrier

concentration and applicability of the Shockley-Read-Hall statistics. We apply this model to study SiC Schottky junction differential admittance behavior as a function of temperature, measurement ac signal frequency and amplitude, and doping occupation number. We compare the results obtained using the new model with those of the traditional models based on the small-signal and truncated space charge approximations. SiC Schottky devices have been fabricated and will be used to obtain the admittance data, which will be compared with the theoretical model. This work was supported by the Office of Naval Research, Grant No. N0014-98-1-0824, Dr. C. Wood program manager.

9:00 AM, Q4

Low Temperature Ohmic Contacts for Vertically Conducting III-N Light Emitting Devices over SiC: V. Adivarahan¹; M. Shatalov¹; A. Lunev¹; G. Simin¹; J. Yang¹; M. Asif Khan¹; R. Gaska²; M. Shur²; ¹University of South Carolina, Dept. of ECE, 301 S. Main St., Rm. 3A80, Columbia, SC 29208 USA; ²Sensor Electronic Technology, Inc., Latham, NY 12110 USA

We present a new low temperature ohmic contacts to SiC for vertical geometry GaN/InGaN light emitting diodes (LEDs) and laser diodes (LDs) grown over SiC substrates. The need for low resistive ohmic contacts to SiC is crucial for the realization of vertically conducting GaN devices. Typically ohmic contacts to SiC require the annealing temperature above 950°C to form NiSi layer. However, it was shown recently that high temperature annealing reduces significantly the QW emission. It is therefore extremely important to obtain low temperature ohmic contacts for GaN/InGaN MQW devices. Our approaches to low temperature ohmic contacts to SiC include a new Al/Ni/Ti/Au metallization scheme and the use of MOCVD deposited n-GaN as a contact layer. GaN/InGaN MQW LED structure grown over SiC substrates by MOCVD technique was used for this experiment. The top p-ohmic contact is fabricated with Pd/Ag/Au annealed at 850°C (5 min.) in N₂ ambient. Sample I with Ni/Al/Ti/Au contact annealed at 950°C in N₂ was used as a reference. Sample II has Al/Ni/Ti/Au annealed at 750°C for 5 min in N₂ ambient. For sample III MOCVD grown n-GaN layer was deposited on the back of SiC substrate followed by regular Ti/Al/Ti/Au ohmic contact. We then compared the p-n junction current-voltage characteristics for the three samples. The reference sample I has the turn-on voltage of about 3V and the differential resistance Rd of 26 Ohm. Sample II has the same turn-on voltage, however Rd is about 2 times higher. For the sample III additional 1-1.5V turn-on voltage was measured with Rd value the same as for reference sample. From this comparative study we conclude that epitaxially grown GaN contact layer gives additional barrier on the SiC-GaN interface but does not contribute to the value of vertical differential resistance. Al/Ni/Ti/Au contact is linear, however it's contact resistance is higher than that of base line Ni/Al/Ti/Au contact. Both our new ohmic contact schemes for SiC allow keeping the highest annealing temperature below 750°C which improves considerably the emission from GaN/InGaN based MQWs.

9:20 AM, Q5

Low Resistivity Ohmic Contacts to Phosphorus Ion-Implanted 4H-SiC Accomplished without Post-Deposition Annealing: Satoshi Tanimoto¹; Junji Senzaki¹; Yasuaki Hayami¹; Masakatsu Hoshi¹; Hideyo Okushi²; ¹R&D Association for Future Electron Devices, Adv. Power Devices Lab., c/o Electrotech. Lab., 1204 1-1-4 Umezono, Tsukuba, Ibaraki 305-8568 Japan; ²Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba, Ibaraki 305-8568 Japan

It is commonly known that the optimal performance of electron devices is closely dependent on the quality of ohmic contacts. A widely used technique to form a region of low contact resistance on SiC is deposition of electrode materials such as Ni and post-deposition annealing (PDA) at high temperature, typically 950°C. However, it has been pointed out that PDA results in the deterioration of electrode surface morphology and an increase in leakage current of thin gate oxides in MOSFETs. Recently, an interesting alternative method that eliminates PDA and heavy impurity doping such as by ion implantation was proposed by Teraji et al. Their method involves growth and removal of thermal oxides followed by immersion in boiling deionized water, and Ti/SiC contacts showing a contact resistance of 5×10^{-3} ohm-cm² were demonstrated on an n-type 6H-SiC(0001) epitaxial layer. However, the ohmic property obtained was still insufficient for practical use. With an eye toward further reducing the contact resistance, it is worthwhile examining contacts to high-dose implanted layers. Ohmic contacts to implanted

layers are indispensable to the fabrication of planar SiC devices since implantation is a crucial means of selective-area doping. In this research, low resistivity titanium ohmic contacts to phosphorus ion-implanted 4H-SiC(0001) were accomplished without PDA. An adequate process for fabricating TLM test structures was carefully designed and carried out, which included P⁺ implantation and activation, mesa etching, field oxide growth, opening of contact windows, and formation of Ni/Ti/SiC contacts by electron beam evaporation and patterning. Superior linearity in I-V characteristics between contacts and specific contact resistance in the range of 10^{-6} ohm-cm² were observed. Additionally, the structure of Ni/Ti/SiC contacts was also characterized by cross-sectional TEM and depth-profiling SIMS. This work was performed under the management of FED as a part of the MITI New Sunshine Program (R&D of Ultra-Low-Loss Power Device Technologies) supported by NEDO.

9:40 AM Break

10:20 AM, Q6 +

Effect of Implant Anneal and Oxidation Conditions on Nitrogen and Phosphorus Implanted 4H-SiC MOSFETs: Sujit Banerjee¹; Kiran Chatty¹; T. P. Chow¹; R. J. Gutmann¹; ¹Rensselaer Polytechnic Institute, Ctr. for Integrat. Electro. and Electro. Manufact., 110 8th St., Troy, NY 12180 USA

Power MOSFETs in 4H-SiC are expected to outperform comparable silicon devices since a shorter drift region is required to block high voltages. Since performance is severely limited by poor inversion layer mobility, current research is focused on improving this parameter in 4H-SiC MOSFETs. While 4H-SiC MOSFET research has emphasized long channel ($L_{ch} \sim 30$ -100 μ m) devices in order to study channel component of the on-resistance in detail, shorter channel lengths (1-10 μ m) are necessary for device applications. In this work, 4H-SiC MOSFETs have been fabricated with channel lengths of 4 and 6 μ m to investigate the effect of implant anneal temperature and oxidation conditions on the field effect mobility, sub-threshold slope and interface state density. MOSFETs with both linear and circular geometries were fabricated on p-type epilayers, with nominal epi-thickness and doping of 10 μ m and 4×10^{15} cm⁻³ respectively. The source/drain regions were implanted with nitrogen or phosphorus and annealed at 1200°C or 1600°C. Ni-based source/drain contacts were annealed at 1000°C for two minutes in argon. The gate oxide on the samples with phosphorus implanted source/drain was a low temperature deposited oxide, which underwent a two-step re-oxidation anneal at both 1100°C and 950°C. The MOSFETs on the two samples indicate similar threshold voltages (~ 10 V) and sub-threshold slopes (~ 2.5 V/decade). The high sub-threshold slope is attributed to the large density of interface states ($\sim 7.8 \times 10^{12}$ eV⁻¹cm⁻²). The field-effect mobility extracted from the peak transconductance values are ~ 0.5 cm²/V-s and ~ 6 cm²/V-s for phosphorus implanted samples annealed at 1200°C (sample A) and 1600°C (sample B) respectively. MOSFETs with phosphorus-implanted source/drain, annealed at 1200°C were also fabricated with variations of above mentioned gate oxide process, yielding a field-effect mobility of ~ 9 cm²/V-s. The higher mobility in sample C is attributed to the loading/unloading and temperature ramp-up/ramp-down of the sample in the oxidizing ambient. Nitrogen implanted source/drain MOSFETs, annealed at 1600°C yielded field-effect mobilities of ~ 3 cm²/V-s (sample D). The gate oxide and re-oxidation anneal conditions were similar to samples A and B. Preliminary investigation indicates that the lower mobility values for sample D is due to the larger sheet resistance of the nitrogen implants compared to the phosphorus implants (large source/drain resistance). These results indicate that comparable field-effect mobilities can be achieved with 1200°C and 1600°C implant annealing. Loading/unloading of the samples at 800°C in wet ambient significantly impacts the field-effect mobilities. Detailed characterization and comparison of the interface state density of the samples and the temperature dependence of the device characteristics will be provided at the conference. Acknowledgements: The authors gratefully acknowledge the support of this work by DARPA under grant no. MDA-972-98-C-0001, Center for Power Electronic Systems (NSF Engineering Research Center under award no. EEC-9731677), Philips Research, Briarcliff Manor, NY and MURI of the Office of Naval Research under contract no. N00014-95-1-1302.

10:40 AM, Q7 +

N-Type Doping of 4H-SiC with Phosphorus Co-Implanted with C, Si and N: Zhi Li¹; Lin Zhu¹; T. P. Chow¹; ¹Rensselaer Polytechnic

Institute, Electro. Comp. and System Eng., 110 8th, Troy, NY 12180 USA

Implantation for doping is a critical process step in the fabrication of semiconductor devices. Previously, phosphorus has been shown to be a much better dopant than nitrogen in 4H-SiC for heavily doped n-type implantation. In this paper, the effect of co-implantation of phosphorus with carbon, silicon or nitrogen is studied. Electrical measurements include sheet resistance and Hall measurements as well as forward and reverse I-V characterization of the resulting n+/p junctions. Surface roughness analysis after high temperature annealing is also presented. Si sublattice sites in SiC are regarded as more electronically active than the C sites. The effect of coimplantation of P/C and P/Si on the electrical activation of phosphorus has been monitored. After high temperature (>1400°C) annealing, the sheet resistance is found to decrease more for the P/C sample than the P/Si sample. After 1700°C anneal, respective sheet resistance values of 111 and 132 Ohms/square were measured. The co-implanted C or Si competes with P in recombining with a limited number of Si and C vacancies. After longer annealing cycle or higher temperature, excessive C interstitials could reduce the C vacancies via their recombination during annealing, which raises the probability that implanted P atoms recombine with Si vacancies and reside at Si sublattice sites. In contrast to C, Si could retard P to stay at Si sites. When activation annealing is performed in argon, considerable surface roughening and macrostep formation has been observed, particularly at temperatures > 1600°C. Formation of a roughened surface will decrease the carrier mobility and increase reverse leakage current of n+/p junction rectifiers. Co-implanted phosphorus 4H-SiC rectifiers were fabricated and characterized and compared with phosphorus-implanted ones. Both co-implanted samples have a larger leakage current than P-implanted devices (10⁻⁶ vs. 10⁻⁷ A/cm²). From the forward I-V characteristics, ideal factors of 2.06 and 1.64 were extracted respectively for P/C and P/Si samples, compared to 1.28 for the phosphorus-only sample.

11:00 AM, Q8

High Temperature SiC Implant Activation in a Silane Ambient to Reduce Step Bunching: *Galyna Melnychuk*¹; Tami Issacs-Smith²; John R. Williams²; Alex J. Hsieh³; Jeffrey B. Casady¹; Stephen E. Saddow¹; ¹Emerging Materials Research Laboratory, Depts. of Elect. and Comp. Eng., 216 Simrall Hall, P.O. Box 9571, Mississippi State, MS 39762 USA; ²Auburn University, Phys. Dept., Leach Sci. Ctr., Auburn, AL 36849 USA; ³Army Research Laboratory, Weapons and Matls. Rsch. Direct., Aberdeen Proving Ground, MD 21005 USA

The mechanical strength of silicon carbide does not permit the use of diffusion as a means to achieve selective doping as required by most electronic devices, since diffusion rates in SiC are simply too low to permit this approach. While epitaxial layers may be doped during growth, ion implantation is needed to define such regions as drain and source wells, junction isolation regions, etc. Indeed, SiC is primarily an epitaxial technology where ion implantation is used to selectively dope regions in the epitaxial layer to implement a specific device structure. While ion implantation has been studied in all of the silicon carbide polytypes, ion activation has resulted in serious crystal damage, as these activation processes must be carried out at temperatures on the order of 1600°C. Ion implanted silicon carbide that is annealed in either a vacuum or an argon environment usually is usually characterized by a surface morphology that is highly irregular due to the out-diffusion of Si atoms. We have developed and report a successful process of using silicon overpressure, provided by silane in a CVD reactor during the anneal, to prevent the destruction of the silicon carbide surface. The process has proved successful for p-type implants (Al) and n-type (P) in both 4H and 6H-SiC epitaxial layers. This process has proved to be robust and has resulted in a high degree of ion activation at an annealing temperature of 1600°C without evidence of step bunching at the surface that is believed to be caused by the out-diffusion of Si atoms at the surface. The process has been successfully developed in a 75 mm CVD reactor vessel, thus permitting the activation of ion implanted regions in whole-wafer device lots. To date, numerous anneals have been performed on FET and bipolar structures, the most recent being guard rings to provide surface termination in power diodes. In all cases, the resulting surface morphology was excellent, and it is anticipated that pending device performance data will further prove the utility of our approach. In this paper, the silane overpressure annealing process that has been developed will be described along with any device data generated to date.

11:20 AM, Q9

Formation and Annealing of Ion-Implantation-Induced Defects at Low Temperatures in 6H-SiC: *W. Jiang*¹; W. J. Weber¹; ¹Pacific Northwest National Laboratory, P.O. Box 999, Richland, WA 99352 USA

The formation of defects on both the Si and C sublattices in silicon carbide (SiC) by ion implantation and the thermal or dynamic recovery of these defects at low temperatures have been extensively investigated. The goals of the work are to develop fundamental understanding and predictive models of the dynamic processes affecting the accumulation and recovery of ion-implantation damage in SiC. Such understanding and models will contribute to the advancement of technological applications for SiC. Using a variety of ion species, ion implantation of 6H-SiC single crystals has been performed over the temperature range from 100 to 870K. Ion fluences were chosen to produce implantation damage that ranged from dilute point-defect concentrations to a fully amorphous state. Both conventional 2.0 MeV He⁺ Rutherford backscattering spectrometry (RBS) and a combination of 0.94 MeV D⁺ RBS and nuclear reaction analysis (NRA) in a channeling geometry have been used to characterize the disorder on both the Si and C sublattices in the implanted SiC. Isochronal annealing has also been performed on implanted samples over the temperature range from the implantation temperatures to 1170K. After each annealing step the remaining disorder was determined by the same ion beam techniques. The results show that the damage accumulation follows a sigmoidal dependence on dose, which is consistent with model predictions. At low doses, more C disorder is generated per ion, which is consistent with computer simulations that predict a lower threshold displacement energy on the C sublattice. At higher doses, less residual C disorder is observed, indicating that more C disorder can be simultaneously recovered during implantation. The dependence of the disordering rate and the amorphization dose on the ion species and implantation temperature has been studied. In general, less damage is produced by lighter ions at increasing temperatures because the smaller damage energy densities produce a greater fraction of Frenkel pairs that readily recover. Significant recovery of disorder on both sublattices occurs at room temperature for SiC implanted with Au²⁺ and Si⁺ at low temperatures (170K). However, relatively low thermal recovery rates for He⁺ and C⁺ implanted SiC have been observed and are attributed to the implants trapping at defects in the crystal structure. In-situ RBS and NRA channeling analysis indicates that there are two distinct recovery stages on both the Si and C sublattices in Au-implanted SiC. The recovery stages occur at temperatures between 170 and 300K and between 420 and 570K. The activation energies for these recovery processes are on the order of 0.25 eV and 1.5 eV, respectively. This study was supported by the Office of Basic Energy Sciences, U.S. Department of Energy under Contract DE-AC 06-76RLO 1830.

11:40 AM, Q10 Late News

Session R. Silicon Integration: Thin Oxides, Alternate Dielectrics and Epitaxial Metals

Thursday AM Room: Centennial Halls
June 22, 2000 Cafeteria

Session Chairs: Patrick M. Lenahan, Pennsylvania State University, Dept. ESM, University Park, PA 16802 USA; Alex Demkov, Motorola, Inc., Prod. Sect. MD M3602200, Mesa, AZ 85202 USA

8:00 AM, R1 *Invited

Reliability Characterization and Projection Issues of Sub-3nm Gate Oxides: *John S. Suehle*¹; ¹National Institute of Standards and Technology, Semicond. Elect. Div., Gaithersburg, MD 20899 USA

The reliability of SiO₂ gate dielectrics has received much attention as film thickness is scaled below 3.0 nm. Soft breakdown behavior, wider

failure distributions, and non-Arrhenius temperature acceleration present new challenges in reliability characterization and assessment. The occurrence of soft or “quasi” breakdown has been reported to be related to test conditions, device gate area, and thickness and is generally believed to be due to decreased power dissipation during the breakdown event. Traditional reliability testing methods must be modified to include robust techniques for breakdown detection in ultra-thin films exhibiting soft or quasi breakdown characteristics. Published standard test procedures fail to detect breakdown in films thinner than 4.0 nm. Techniques that monitor current/voltage noise or periodically measure low voltage leakage current are effective in detecting breakdown in films as thin as 2.0 nm. Recent reports have shown that time-dependent-dielectric-breakdown voltage and temperature acceleration parameters can be similar or different for hard and soft breakdown modes depending on the breakdown criterion used. It is important that the first event detected in the current versus time characteristics be used as the breakdown criterion for obtaining consistent acceleration parameters. The damaged region that occurs at breakdown in an ultra-thin film is believed to be a localized percolation path that is independent of gate area and exhibits a power-law conductance behavior. The physical mechanism of defect generation and oxide wear-out of thin SiO₂ films is still under investigation. There does not appear to be a substantial difference in the breakdown mechanism between ultra-thin and thicker films. Recent studies indicate that defect generation and wear-out due to substrate hot-carrier injection (SHEI) and high field stress are similar processes. Combined SHEI and constant voltage stress measurements indicate that the number of defects at breakdown is independent of the stress condition indicating a carrier-induced breakdown mechanism.

8:40 AM, R2

Leakage Currents in Thin Oxides and Nitrided Oxides: *Patrick M. Lenahan*¹; *Jeremy J. Mele*¹; *Michael S. Liu*²; *R. K. Lowry*³; *Dustin Woodbury*³; ¹Penn State University, Dept. ESM, 227 Hammond Bldg., University Park, PA 16802 USA; ²Honeywell, Inc., Plymouth, MN 55441 USA; ³Intersil Corporation, Melbourne, FL 32902 USA

“State of the art” metal-oxide-silicon gate oxides can be less than 10nm thick. In such very thin oxides, stress induced leakage currents (SILC) can be an important, possibly fundamental, limiting concern. These currents are the result of inelastic tunneling of electrons through deep levels in the oxides close to the Si/SiO₂ boundaries. Several groups have suggested that E’ centers oxygen deficient silicons back bonded to three oxygens in the oxide, are the defects responsible for the inelastic tunneling phenomena. A recent study compared leakage current density versus voltage and electron spin resonance (ESR) measurements on relatively thick (~100nm) oxides. In that study, neutral E’ centers were generated in thick oxides by exposing the oxides to vacuum ultraviolet (VUV) light. The E’ generation was accompanied by the generation of large oxide leakage currents. Brief low temperature (200°C) anneals in air annihilated most of the E’ centers and also eliminated most of the leakage currents in these oxides. We have extended the observations of that study to three sets of quite thin oxides and nitrided oxides approximately 5.8nm thick. The response of all three thin dielectric films is qualitatively similar to that of the much thicker films. The VUV exposure generates strong leakage currents, the brief 2000°C anneal eliminates most of the leakage currents. ESR measurements on the thin films are also qualitatively similar to measurements made on the thick films. In both thick and thin dielectric films we observe the simultaneous generation of E’ centers and leakage currents. However, due to the extremely small volumes of SiO₂ in the thin oxide measurements, we have not yet made detailed quantitative comparisons of E’ density and leakage currents in the thin oxides. We note significant differences in the leakage currents in the differently processed oxides and will offer reasonable speculation with regard to the cause of these differences.

9:00 AM, R3

Characteristics of Ultrathin SiO₂ Film Formed on Si (100) using Concentrated Ozone Gas: *Kunihiko Koike*¹; *Shingo Ichimura*²; *Akira Kurokawa*²; ¹Iwatani International Corporation, 4-5-1 Katsube, Moriyama, Shiga 524-0041 Japan; ²Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba, Ibaraki 305-8568 Japan

Ozone is expected to be a promising oxidizing reagent for the fabrication of future ultrathin gate oxide film. We have investigated the characteristics of the ozone oxidation on Si(100) substrate with highly concen-

trated ozone gas (up to 30 vol%) and compared it with oxidation by oxygen. In this report, we clarify the superior features of ozone oxidation from the view point of the growth rate of the oxide film, suboxide states at the Si/SiO₂ interface, and the quality of the synthesized SiO₂ film. A SiO₂ film as thick as 2.8 nm grew at 600°C (J and 8 Torr in a 10 min exposure with 20 vol% ozone gas, while under the same experimental conditions only a 1.1 nm thick SiO₂ film could be formed on the same Si substrate with oxygen. The oxide film growth by ozone was linearly proceeded with the oxidation time in excess of 90 min. In contrast, the oxide film growth saturated within 10 min in the oxidation by oxygen, and it was impossible to form a thicker oxide film more than 1.1 nm in a 90 min exposure. The difference between the oxidation by ozone and oxygen may be explained from diffusion species in SiO₂ film and reaction species at the Si/SiO₂ interface. Atomic oxygen dissociated from ozone molecules on the surface, which should have larger diffusion coefficient, may be predominant in the oxidation by ozone, while only diatomic oxygen molecules diffuse into the Si/SiO₂ interface to contribute oxidation reaction in the oxidation by pure oxygen. In addition, we confirmed that the oxide film fabricated by ozone has superiority in the film quality over thermally grown oxide film fabricated by a conventional method. Suboxides near the Si/SiO₂ interface were determined by x-ray photoelectron spectroscopy (XPS). The results indicated the oxide film formed by ozone has smaller amount of the suboxides than the oxide formed by oxygen, in spite of the fact that the ozone oxidation was performed at a lower substrate temperature than the oxygen oxidation. We also investigated the film density using its etching speed by diluted HF solution. The etching rate for the ozone oxide film did not change from the surface to the interface. In contrast, when thermally grown oxide was etched to less than 1 nm thickness, the etching rate slowed. We speculate that this result is due to the existence of the structural transition layer.

9:20 AM, R4

On the Density of States of Pb₁, Si/SiO₂ Interface Centers: *Tetsuya D. Mishima*¹; *Patrick M. Lenahan*¹; ¹Penn State University, Dept. ESM, University Park, PA 16802 USA

A high percentage of Si/SiO₂ interface states are associated with silicon “dangling bond” defects called Pb centers. At the technologically important (100) Si/SiO₂ interface, two Pb center variants appear, Pb₀ and the Pb₁. Although structure and electronic properties of the Pb₀ center are fairly well established, the electronic properties of the Pb₁ remain controversial, with two quite different points of view in the literature. Some time ago, Gerardi et al argued that the Pb₁ variant has two levels near the middle of the silicon band gap with an electron correlation energy of approximately 0.3eV. Stesmans and Afanas’ev have quite recently argued to the contrary, that Pb₁ centers do not have levels in the silicon band gap. We have strong evidence that the original contention of Gerardi et al, that Pb₁ centers do have levels in the gap is correct. Our results also suggest strongly that the Pb₁ correlation energy is significantly smaller than that of the more well understood Pb₀ center. Our evidence comes from spin dependent recombination (SDR)[4] measurements of hot carrier and gamma irradiated MOSFETS, which (after stressing) have been configured as gate controlled diodes. In SDR one configures a device so that the device current will be dominated by recombination. Recombination events are typically electron spin dependent. By measuring a recombination dominated current while simultaneously exposing a device to a slowly varying magnetic field and microwave radiation at a frequency appropriate for electron spin resonance (ESR) of a deep level, one can identify the structure of the deep level in question. (The SDR spectrum is essentially identical to the ESR spectrum of the defect in question.) We have made SDR measurements of both Pb₀ and Pb₁ centers as a function of MOS gate bias and of source/drain to substrate forward bias potential. The signal to noise ratio in our measurements has been quite high, sufficient to clearly identify components of the spectra associated with the electron-nuclear hyperfine interactions of the 4.7% of Pb₁ and Pb₀ sites associated with ²⁹Si atoms. Our results, almost by definition, demonstrate that the Pb₁ centers do indeed have levels in the Si band gap. Our results also strongly suggest that the Pb₁ electron correlation energy is considerably smaller than that of the Pb₀. Our results thus strongly support the original arguments of Gerardi et al and we believe help to resolve the controversy with regard to the energy levels of this center.

9:40 AM Break

10:20 AM, R5 *Invited

Alternative Gate Dielectrics for Advanced CMOS Devices: Gerald Lucovsky¹; ¹North Carolina State University, Depts. of Phys. Elect. and Comp. Eng., Matls. Sci. and Eng., Raleigh, NC 27695-8202 USA

The aggressive scaling of CMOS devices with lateral dimensions <10 nm requires gate dielectrics with equivalent oxide thickness, EOT, <1.5 nm. This is a thickness regime in which direct tunneling through thermally-grown SiO₂ becomes much greater than 1 A-cm⁻² mandating the introduction of alternative deposited gate dielectrics that can significantly reduce direct tunneling. One obvious approach is to substitute non-crystalline insulators with dielectric constants, k , greater than SiO₂ ($k_{ox} \sim 3.8$), to obtain physically-thicker films with the same capacitance as the physically-thinner SiO₂ layers. The increased physical thickness for this direct dielectric substitution scales with the ratio of the dielectric constants, k/k_{ox} . Since tunneling current decreases exponentially with increasing thickness, alternative gate dielectrics with $k > (2-3)k_{ox}$ are anticipated to produce significant reductions in direct tunneling. However, the tunneling transmission probability also depends on i) the height of the tunneling barrier, E_b , e.g., the conduction band offset energy, between the Si substrate and the alternative dielectric, and ii) the effective mass of electrons, m_e^* , tunneling through the alternative dielectric. Since band-gaps and dielectric constants generally scale inversely with each other, increased physical thickness alone is not sufficient to insure the many order of magnitude decreases in tunneling current required for the scaled performance and reliability of advanced CMOS devices with EOT ~ 1 nm or less. In addition, the direct deposition of many high- k oxides and silicates onto hydrogen terminated Si (or so-called HF-last) substrates is frequently accompanied by substrate interactions that produce lower- k interfacial oxides and silicates thereby decreasing the gate dielectric capacitance and/or introducing electrically-active defects. One approach to this problem to use composite dielectrics with pre-deposition processed interfacial layers such as ultra-thin nitrided SiO₂. These interfacial layers must suppress substrate interactions that can occur during film deposition, and at the same time maintain interfacial electrical properties and reliability equivalent to those of thermally-grown Si-SiO₂. The incorporation of these interfacial layers significantly reduces the minimum attainable values of EOT. For example, experiments to date indicate that interfacial nitride oxides ~ 0.5 - 0.6 nm thick, introduce about 0.35 nm of EOT into a stacked gate dielectric. These composite gate dielectric structures also introduce a second dielectric interface into the gate stack: i.e., the internal interface between the 'interfacial' nitride oxide and the 'bulk' alternative dielectric. This paper addresses materials issues associated with multi-layer, stacked dielectrics, including i) separate and independent processing for gate stack formation, ii) bulk film and interface physical and chemical characterizations, and iii) physical mechanisms that determine the limiting interfacial bonding structure and resultant electrical properties. Finally, the paper presents a conceptual framework for correlating chemical bonding in elemental and compound oxides with many of the bulk and interfacial properties that are critical in determining gate stack performance and reliability in aggressively scaled CMOS devices.

11:00 AM, R6

Optimization of a Silicon Oxide-Nitride Stack for Gate Dielectric Applications: Arun Karamcheti¹; Husam N. Al-Shareef¹; Tien-Ying Luo¹; Victor H.C. Watt¹; Kenneth J. Torres¹; Michael D. Jackson¹; Howard R. Huff¹; ¹SEMATECH, Inc., Front End Process., 2706 Montopolis Dr., Austin, TX 78741 USA

Silicon oxide-nitride stacks have attracted significant attention in recent years as viable alternatives to SiO₂ for the gate dielectric. These composite stacks offer the potential of a higher dielectric constant and, therefore, lower leakage currents than an oxide of equivalent thickness. In addition, the presence of nitrogen improves the gate dielectric resistance to boron penetration from the p⁺ doped poly-silicon gate electrodes in PMOS devices. In this paper, we examine optimizing the oxide-nitride stack by modifying the process conditions for the formation of the individual layers and their composite anneal with the goal of obtaining the thinnest possible oxide-nitride stack that is electrically stable for gate dielectric purposes. It is expected that the extensive material and electrical characterization performed will lead to a better understanding of the behavior of such stacks and can complement previously docu-

mented structures. The film stacks were deposited in a single-wafer, rapid thermal processing (RTP)/rapid thermal chemical vapor deposition (RTCVD) cluster tool. Prior to deposition, the wafers were cleaned via two different conditions: RCA Clean or HF last. The surface quality of these films was characterized both before and after processing using atomic force microscopy (AFM). The initial layer in the stack was an oxide grown in NO at two different temperature (700°C, 800°C)-time (10 sec, 20 sec) combinations. This was followed by CVD deposition of Si₃N₄ from a mixture of SiH₄ and NH₃. The nitridation temperature (700°C, 750°C, and 800°C), time (10 sec, 20 sec, and 30 sec), and SiH₄:NH₃ ratio (1:30, 1:40, and 1:50) were varied. As a final step, the stack was annealed in NH₃ at 950°C followed by an N₂O anneal at three different temperatures (750°C, 850°C, and 900°C). For electrical characterization, the stack was capped with a 200 nm amorphous silicon layer and patterned into capacitor dots. The results from capacitance-voltage (C-V), current-voltage (I-V), and reliability measurements of the capacitance structures, including equivalent oxide thickness (EOT), hysteresis (ΔV_{FB}), leakage current density (J_g), charge to breakdown (Q_{bd}), stress-induced leakage current (SILC), time-dependent dielectric breakdown (TDDB), etc., will be presented. Blanket films have also been physically characterized for thickness and uniformity using a spectroscopic ellipsometer. Secondary ion mass spectrometry (SIMS) data for the nitrogen profile and transmission electron microscopy (TEM) data for measuring the physical stack thickness will also be presented.

11:20 AM, R7

Investigation of Implant and Anneal Modified Thermally Grown SiO₂: John F. Conley¹; Christopher J. Nicklaw²; Edward Taw¹; ¹Dynamics Research Corporation, Adv. Tech. Grp., 1055 Shafter St., San Diego, CA 92106 USA; ²Vanderbilt University, EE, Nashville, TN USA

The past few years have seen increased interest in the properties of defect engineered thin SiO₂ films, particularly those films modified via ion implantation and annealing. It has been reported that implanted and annealed films exhibit novel properties such as luminescence and reversible charging, making them candidates for optoelectronics applications and non-volatile memory devices 2,3 It has also been suggested that implant generated defects can be used to charge compensate the positively charged defects intrinsic to thermally grown SiO₂.4 Despite this widespread interest, 1-4 a physical understanding of the electronic and structural properties of the active defects in implant and anneal modified oxide films remains elusive. In this abstract, electron spin resonance (ESR) and capacitance vs. voltage measurements (CV) are used to investigate thermally grown oxides modified by Si implantation and subsequent annealing. (Si was chosen in order to study the effects of implant damage without a chemical effect.) A control oxide sample was neither implanted nor annealed. Strong evidence is presented indicating that implantation generates electron traps in SiO₂. These electron traps (a) appear to have a large capture cross section, the density approaches saturation after injection of less than 10¹³ electrons/cm², (b) are electrically stable at room temperature for a period of at least two weeks, and (c) once negatively charged, have a large capture cross section for holes. The implant induced generation of electron traps is accompanied by the creation of defects known as E' centers. The structure of the E' center is that of an unpaired electron on a Si atom that is back-bonded to three oxygen atoms. E' centers have been shown to dominate trapping in thermally grown SiO₂ and are typically associated with positive charge. Results are presented suggesting that E' centers can act as both electron and hole traps in these oxides. E'-type defects are modeled using density functional theory (DFT).5 Finally, strong evidence is presented that the implant induced electrons traps can charge compensate positive trapped charge in irradiated SiO₂.

11:40 AM, R8

Theoretical and Experimental Investigation of Ultra-Thin Oxynitrides and the Role of Nitrogen at the Si-SiO₂ Interface: A. Demkov¹; R. Liu¹; X. Zhang¹; H. Loehelt¹; ¹Motorola, Inc., Semiconductor Prod. Sect., MD M360, 2200 W. Broadway Rd., Mesa, AZ 85202 USA

The International Technology Road Map for Semiconductors states that the usual scaling of CMOS devices will stop about the year 2012. The main reason for this is not the lithography scaling problems as was previously thought, but rather the leakage through the silicon dioxide gate with a thickness below 4 nm. The modification of the oxide layer to improve the dielectric constant coupled with the understanding of the

microscopic nature of the leakage may extend the current materials technology for a few device generations, before we will ultimately have to switch to a high-k gate dielectric. Silicon Oxynitrides SiO_xN_y are important in many applications in the semiconductor industry. Most often they are observed in the interfacial regions e.g. between the oxide and the nitride. The properties of these thin layers are not yet well understood, and even the very thermodynamic stability of the material is questioned. Perhaps, some of the most important questions are the nitrogen distribution at the interface, and the effect of nitrogen on the atomic structure and ultimately on the transport properties such as a band offset and electron mobility. To achieve a better understanding of these effects we use a combination of the infra-red ATR and ab-initio electronic structure methods. We use a theoretical structural model of the Si-SiO₂ interface with the oxide thickness of 0.8 nm [1]. The interfacial region amounts to about 0.4 nm (the total thickness of the oxygen containing layer is 1.2 nm). The Density Functional Quantum Molecular Dynamics simulations suggest that N accumulates at the interface. The physical reason for this is the chemical nature of nitrogen. Nitrogen prefers a three-fold coordinated structure, which is impossible to realize within the oxide layer without the introduction of defects. We have generated samples with the nitrogen concentrations from $1.69 \times 10^{14} \text{ cm}^{-2}$ to $6.78 \times 10^{14} \text{ cm}^{-2}$. The structural analysis of the nitrogen containing structure indicates a significant improvement of the oxide layer and the interface. We have performed a calculation of the vibrational density of states. A N-localized mode at 809 cm^{-1} has been identified. The experimental infrared ATR data is in qualitative agreement with the calculation. The valence band offset calculations revealed a 0.3 eV increase of the offset due to nitrogen at the highest nitrogen concentration considered. As a result a 0.8 nm oxynitride is equivalent to a 1.2 nm pure oxide. The valence band offset increase comes mainly from the structural change in the oxide layer. The interfacial dipole contributes 0.12 eV to the increase, while the structural change in the oxide layer gives additional 0.2 eV. We describe the leakage current in an ultra thin MOS structure. The Landauer transmission matrix theory is used to model the conductance through the gate. We investigate the effects of the local atomic structure changes, caused by the presence of nitrogen at the interface, on the electric properties of this fundamental element of the CMOS technology. This is an example of the "bottom up" engineering, where a combination of the materials and quantum transport theories can make a real impact. We compare our exact results with those obtained within the WKB approximation for a barrier structure computed for our model heterojunction using the method of [1]. We show that a defect free Si-SiO₂ interface may result in a dramatic change in the leakage current.

Session S. Transparent Conducting Oxides II - Films

Thursday AM Room: Centennial Halls
 June 22, 2000 Main Lounge

Session Chairs: Alex Zunger, National Renewable Energy Laboratory, Golden, CO 80401 USA; Thomas Mason, Northwestern University, Evanston, IL 60208 USA

8:00 AM, S1 *Invited

Growth Process-Doping-Microstructure-Charge Transport Relationships in Transparent Conducting Oxide Thin Films: *Anchuan Wang*¹; Nikki L. Edelman¹; Jason R. Babcock¹; T. J. Marks¹; M. Yan²; R. P.H. Chang²; Melissa A. Lane³; Paul W. Bazis³; Carl R. Kannewurf³; Paul A. Lee⁴; Neal R. Armstrong⁴; ¹Northwestern University, Chem. Dept. and the Matls. Rsch. Ctr., 2145 Sheridan Rd., Evanston, IL 60208-3113 USA; ²Northwestern University, Dept. of Matls. Sci. and Eng. and the Matls. Rsch. Ctr., Evanston, IL 60208-3113 USA; ³Northwestern University, Depts. of Elect. and Comp. Eng. and the Matls. Rsch. Ctr., 2145 Sheridan Rd., Evanston, IL 60208 USA; ⁴University of Arizona, Dept. of Chem. and the Opt. Sci. Ctr., Tucson, AZ 85721 USA

Transparent conducting oxides (TCOs) have gained increasing importance as key components of numerous display, optoelectronic device, and solar energy technologies. There are constant needs for improved materials as well as better understanding of film growth process/mechanism-microstructure-charge transport relationships. In this report, we compare and contrast the properties of films grown by metal-organic chemical vapor deposition (MOCVD) and pulsed laser deposition (PLD), as well as compare some properties to those of the well-characterized bulk solids. Systems which are discussed here include: Sn-doped Zn-In-O materials, Sn-doped Ga-In-O materials, Cd-Sn-O materials, Cd-In-O materials, and Zn-Sn-O materials. Films grown on a variety of substrates have been characterized by x-ray diffraction, high resolution electron microscopy and selected area electron diffraction, AFM, transmission optical spectroscopy, x-ray and uv photoelectron spectroscopy, as well as variable-temperature Hall effect and four-probe electrical conductivity. What emerges are systems that are microstructurally quite different than the seemingly analogous bulk materials, important conclusions about the importance of grain boundaries for charge transport, transparency windows that are significantly broader than that of ITO, and conductivities that are up to 5x that of ITO.

8:40 AM, S2

A Study of the Amorphous-to-Crystalline Phase Transformation in Indium Tin Oxide: *David C. Paine*¹; Daniel Sparacin¹; Eric Chason¹; Hyo-Young Yeom¹; ¹Brown University, Div. of Eng., 182 Hope St., Providence, RI 02912 USA

The indium oxide crystal structure (bixbyite) is based on the arrangement of two types of non-equivalent InO_6 structural units to form a 80 atom unit cell. In the crystalline form, slightly sub-stoichiometric indium oxide, with or without tin as a substitutional dopant, is a degenerate semiconductor widely used for transparent electrode applications. PVD deposition onto cool (room T) substrates-required for deposition onto heat sensitive polymer substrates-can result in an amorphous structure that crystallizes at remarkably low temperatures (<150°C) relative to the indium oxide melting point (1910°C) in a process that is not yet well understood. The transformation from amorphous to crystalline states is characterized by a fundamental electronic change from a wide band gap semiconductor in the amorphous state to a metal-like degenerate state in the crystalline form. The attendant change in carrier density and mobility determine the conductivity and the plasma absorption edge of indium oxide. These critical properties provide an ideal tool for studying the a/c-transformation which we have used to show that the a/c-transformation occurs in two stages starting with amorphous structural relaxation followed by crystallization. We have studied the a/c-transformation in both DC magnetron sputter and electron-beam deposited indium oxide using isothermal annealing (110 to 250°C) combined with in situ resistivity, in situ reflectivity, TEM, glancing incidence angle x-ray diffraction and in situ wafer curvature measurements. From these measurements we have determined that the structural relaxation of the amorphous phase occurs via a process that is thermally activated ($E_a=1.3 \text{ eV}$) and has a kinetic dimensionality (Avrami parameter) near unity. The amorphous relaxation results in a uniform decrease in the molar volume of the amorphous structure which leads to a significant increase in tensile stress in the film. Subsequent crystallization occurs with a surprising increase in molar volume and a kinetic dimensionality of approximately 3 which is consistent with 2-d nucleation and growth. A model that fully describes the kinetics of transformation has been developed and will be presented along with several potential applications of the low temperature a/c-transformation in indium oxide.

9:00 AM, S3

CdO Thin Films Produced by Metal-Organic Chemical Vapor Deposition with DMC and DMC-THT Precursors: *Xiaonan Susan Li*¹; Dong Schulz¹; Calvin Curtis¹; Timothy Gessert¹; Timothy Coutts¹; ¹National Renewable Energy Laboratory, 5200, 1617 Cole Blvd., Golden, CO 80401 USA

Among the various transparent conducting oxide (TCO) thin films, few studies have been devoted to cadmium oxide (CdO). One reason for this is due to the toxicity of Cd. However, some studies indicate that Cd-containing compounds may have the advantage of enabling a high mobility to be achieved. This is a prerequisite for high conductivity TCO materials with minimal free-carrier absorbance. This paper will report on the fabrication and properties of CdO films made by low-pressure chemi-

cal vapor deposition with dimethylcadmium (DMC) and dimethylcadmiumbis(tetrahydrothiophene) (DMC-THT) precursors. Comparisons between the CdO films formed with two different precursors are made. The material properties were studied using Hall probe measurements, atomic force microscopy (AFM) and secondary ion mass spectrometry (SIMS). We observed that the DMC precursor has a decomposition temperature around 100°-200°C. The deposition rate increases from ~1 nm/min at 100°C to ~10 nm/min at 200°C and achieves a maximum value of 20 nm/min at 300°C (DMCd flow rate was ~1scm). The nucleation process also changes dramatically with deposition temperature (Td). AFM reveals that, at lower Td, small grains are formed producing a smooth thin CdO film. As the Td increases, the nuclei size increases and density decreases. AFM images show that at a Td of 400°C, very large nuclei are formed and the thin film becomes discontinuous. Consequently, the electronic properties of these films vary significantly with Td. The carrier concentration varied from 1019/cm³ at high Td to 1021/cm³ at low Td. Meanwhile the Hall mobility varies from 1.8 cm²/V-s at low Td to 216 cm²/V-s at high Td. To our knowledge this is the largest mobility achieved for CdO in either thin-film or bulk form. For the CdO thin film made from the DMC-THT precursor, there was less sensitivity with Td. The deposition rate varied slowly with Td, which may indicate that the nucleation process was less sensitive to the substrate temperature that used. Conformal CdO films on glass substrate can be formed up to a Td of 550°C. As with the structural property, the variation in electronic properties was smaller than that for the DMCd precursor. Compared to the factor of 100 changes in carrier concentration observed in the DMCd-films, the carrier concentration in the DMC-THT-films varied only from 2x1020/cm³ to 4x1020/cm³. The Hall mobility increased from 5.2 cm²/V-s at low Td to 59.7 cm²/V-s at high Td. However, the decomposition temperature of DMC-THT precursor was about 100°C higher than that for the DMCd precursor, which may bring advantages for development of ternary and mixed oxides.

9:20 AM, S4 +

Growth and Doping of Textured, Phase Pure p-type CuAlO₂ Films: *Renaud Emmanuel Stauber*¹; *John D. Perkins*¹; *Phil A. Parilla*¹; *David S. Ginley*¹; ¹National Renewable Energy Lab, NCPV, 1617 Cole Blvd, SERF E100-15, Golden, CO 80401 USA

CuAlO₂ is a p-type semiconductor with a direct-allowed bandgap of 3.5eV, making it a promising material for p-type transparent conduction and hence applications in flat-panel display electrodes, transparent circuits (as a potential heterojunction partner in all-oxide diodes and transistors), and ultraviolet LED's¹. With a few notable exceptions (SrCu₂O₂², and nitrogen-doped ZnO³) there have been very few reports of p-type transparent conducting oxides. We report on the growth of c-oriented thin films of transparent p-type CuAlO₂. Previously we showed that nearly phase pure CuAlO₂ thin films on sapphire could be grown from a variety of precursors by annealing the films over a mixture of CuO/Al₂O₃ powders in air at 1050°C for 1.5hours⁴. However, this synthesis method suffered from the persistence of various impurity phases (primarily CuAl₂O₄) and significant morphological non-uniformities. We eliminated these problems by changing substrates to cubic zirconium (YSZ) (removing the potential aluminum source from the sapphire) and simultaneously lowering the temperature and oxygen partial pressure during the anneal. Smooth, (00L) textured, and phase pure films were obtained from amorphous precursors deposited at room temperature by RF sputtering with anneals as low as 800°C in flowing argon, though they were somewhat less transparent than films annealed at 940°C in 10T of oxygen. These annealing conditions were determined from temperature-oxygen phase diagrams for Cu-Al-O mixtures with a Cu:Al ratio of one derived from multiple existing phase diagrams. At 940°C and 800°C, CuAlO₂ is not thermodynamically stable in air and will decompose into CuAl₂O₄ and CuO, necessitating reduced oxygen partial pressures. Though the films remained uniaxially textured, because of lattice mismatch problems with YSZ, films over 0.5µm were difficult to grow. Despite the high crystalline quality of the current films, the carrier concentration is still quite low (10¹⁶-10¹⁷ cm⁻³). Our attempts to increase this by substituting small amounts of Mg, and K for Al and N for O have not been successful, although we have grown 2%Mg:CuAlO₂ films retaining the desired CuAlO₂ as determined by x-ray diffraction. We will discuss current attempts to dope this material and other systems of interest. 1. H. Kawazoe, M. Yasukawa, H. Hyodo, M. Kurita, H. Yanagi, and H. Hosono, *Nature* 389, 939 (1997). 2. A. Kudo, H. Yanagi, H. Hosono, and H. Kawazoe, *Applied Physics Let-*

ters 73, 220-222 (1998). 3. K. Minegishi, Y. Koiwai, Y. Kikuchi, K. Yano, M. Kasuga, and A. Shimizu, *J. Appl. Phys.* 36, L1453-L1455 (1997). 4. R. E. Stauber, J. D. Perkins, P. A. Parilla, and D. S. Ginley, *Electrochemical and Solid State Letters* 2, 654-656 (1999).

Session T. InGaAsN and Related Materials

Thursday PM Room: Driscoll Center North
June 22, 2000 Ballroom A/B

Session Chairs: Nelson Li, EmcoreWest, Albuquerque, NM 87123 USA; Steve Kurtz, Sandia National Laboratories, Albuquerque, NM 87185 USA

1:20 PM, T1

Effect of (1,1)-DMHy Purity on MOCVD-Grown InGaAsN Performance and on Post-Growth Annealing Behavior: *Robert M. Siegl*¹; *Andrew A. Allerman*¹; *Steven R. Kurtz*²; *Eric D. Jones*¹; *Olga Blum Spahn*¹; ¹Sandia National Laboratories, 1711, M.S. 0603, Albuquerque, NM 87185 USA

The addition of small amounts of N into InGaAs alloys has the unusual and valuable effect of simultaneously reducing both lattice constant and bandgap. Unfortunately, even small N quantities (<1%) drastically degrade carrier lifetimes, mobilities, and other critical material parameters. While universally observed, the extent to which this degradation is an intrinsic aspect of the InGaAsN quaternary alloy is not yet clear. Strong suspicions have existed that a limiting factor in MOCVD-grown InGaAsN performance is the purity of the 1,1-dimethylhydrazine (DMHy) nitrogen precursor typically used. However, the very strong dependence of InGaAsN properties on growth conditions and alloy content has hindered experimental verification. In this study, we have compared a number of DMHy sources and definitively demonstrate extrinsic material limitations due to the presence of unidentified DMHy impurities. Furthermore, we find post-growth annealing behavior also varies with the DMHy source. This may help explain the different annealing behaviors reported by various groups. We have tested numerous DMHy sources from three different vendors, and have additionally tested multiple bubblers filled from the same batch of DMHy. A combination of relatively high N-content lattice-matched (LM) thick layers (EG~1.05eV, In~7%, N~2.4%) and low N-content QW's (PL emission~1.13-1.17 micron) served as standard test structures. Nitrogen incorporation was found to be independent of DMHy source for both thick layers and QW's. Room temperature PL intensity for as-grown QW samples was very reproducible for a given batch of DMHy, and did not change with DMHy bubbler depletion. However, the PL intensity varied by two orders-of-magnitude between different DMHy sources. The background doping of 0.5 micron LM layers varied by more than an order of magnitude with DMHy source. The lowest background carrier concentrations and the strongest QW PL were obtained from the same DMHy source. We investigated various QW post-growth annealing schedules, ranging from 400-850°C for durations between 10 seconds and 10 minutes under nitrogen. In general, anneals in the range 650-750°C for 20-30 seconds produced the largest intensity improvement accompanied by blueshifts of 0-35 nm, while anneals at 850°C typically degraded PL intensity and caused blueshifts of 25-50 nm. However, these results were also very DMHy source-dependent, with behavior varying from no intensity improvement with post-growth annealing for some sources, to improvements of more than an order-of-magnitude for other sources. Again, strong run-to-run consistency in annealing behavior for samples grown with a given source was observed. In the case of one DMHy source with poor as-grown PL intensity, post-growth annealing brought the intensity up to the level of samples grown with our best DMHy source. In fact, QW samples grown with this source showed an order-of-magnitude or more intensity improvement even for anneals as low as 400°C. The results of this study clearly demonstrate extrinsic, DMHy impurity-related defects are a critical factor in MOCVD

InGaAsN performance, and emphasize that the DMHy source must be a controlled parameter in any meaningful InGaAsN materials study.

1:40 PM, T2 +

Influence of Nitrogen Content and Dopant Type on Deep Level Spectra of MOCVD-Grown InGaAsN: Robert J. Kaplar¹; Aaron R. Arehart¹; Daewon Kwon¹; Steven A. Ringel¹; Andy A. Allerman²; Steven R. Kurtz²; E. D. Jones²; Robert M. Sieg²; ¹Ohio State University, Elect. Eng. Dept., 205 Dreese Lab., 2015 Neil Ave., Columbus, OH 43210 USA; ²Sandia National Laboratories, Albuquerque, NM 87185 USA

Recently, the quaternary semiconductor InGaAsN has attracted considerable interest due to its potential applicability to infrared laser diodes as well as its possible use in high-efficiency solar cells. The InGaAsN alloy may be grown lattice-matched to GaAs such that its bandgap corresponds to emission at the optical-fiber low-loss windows of 1.30 and 1.55 μm ; additionally, the efficiency of multi-junction $\text{In}_{0.5}\text{Ga}_{0.5}\text{P}/\text{GaAs}/\text{Ge}$ solar cells could potentially be improved by the insertion of a lattice-matched, $\sim 1.0\text{eV}$ InGaAsN junction between the GaAs and Ge junctions. Unfortunately, the growth of high electronic quality InGaAsN has been challenging, and to date this material has exhibited high trap concentrations and low minority carrier diffusion lengths. Further, very little is currently known about the nature and sources of traps in both n- and p-type InGaAsN. In this study, potential sources of deep levels in this material have been investigated by examining the influence of nitrogen content and dopant type on the deep level spectra of MOCVD-grown InGaAsN. To study the influence of nitrogen and n-dopant type, the DLTS spectra of unintentionally doped n-type $\text{In}_{0.02}\text{Ga}_{0.98}\text{As}$ and $\text{In}_{0.09}\text{Ga}_{0.91}\text{As}$, Sn-doped n-type $\text{In}_{0.09}\text{Ga}_{0.91}\text{As}$, and lattice-matched 1.05eV and 1.15eV Sn-doped n-type InGaAsN were compared. Each of the InGaAs samples exhibited a mid-gap majority-carrier trap which is believed to be mismatch related, and an additional minority-carrier deep level was present in the spectrum of the Sn-doped InGaAs. Aside from these traps, the DLTS spectra of the InGaAs samples were flat at $\sim 10^{13}\text{cm}^{-3}$, which is the detection limit of our equipment for the samples studied. Majority-carrier spectra of the Sn-doped InGaAsN samples were measured both before and after annealing and varied according to the specific sample structure and growth conditions used, although in general trap concentrations ranged from approximately 10^{13}cm^{-3} to approximately 10^{15}cm^{-3} . The increase in overall trap density as compared to the InGaAs samples suggests that additional defects are introduced by either the presence of nitrogen in the lattice or by impurities in the nitrogen source. Further, minority-carrier traps were detected in some of the Sn-doped InGaAsN samples. Since large amounts of background carbon are typically incorporated into MOCVD-grown InGaAsN, we compared the majority-carrier spectra of unintentionally doped, Zn-doped, and C-doped 1.05eV p-type material both before and after annealing in order to examine the effects of carbon on the deep level spectra. Prior to annealing, the C-doped material exhibited a slightly lower overall trap concentration than the unintentionally doped and Zn-doped samples, while after annealing the spectra of the three samples were virtually identical. Minority-carrier injection experiments resulted in DLTS spectra very similar to the majority carrier spectra. These results suggest that carbon does not introduce deep levels into this material.

2:00 PM, T3

Transport Studies of Compensated InGaAsN Solar Cell Materials: Steven R. Kurtz¹; A. A. Allerman¹; C. H. Seager¹; R. M. Sieg¹; E. D. Jones¹; ¹Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-0603 USA

InGaAsN alloys are being developed as long wavelength materials for laser and multi-junction solar cell applications. Bandgaps of $\leq 1.0\text{eV}$ are obtained for $\text{In}_x\text{Ga}_{1-x}\text{As}_{1-y}\text{N}_y$ for low N concentrations ($y \geq 0.02$), and the quaternary is lattice-matched to GaAs for compositions with $x \approx 3y$. Even at these low concentrations, N incorporation has proven problematic, and device performance has not reached expectations, with radiative efficiencies and minority carrier diffusion lengths diminishing with increasing N concentration. With N atoms producing random alloy fluctuations, the N incorporation might be expected to result in intrinsic localization and a mobility-edge which would result in poor device performance. Since bandstructure calculations predict that N strongly perturbs the conduction band, electrons should be most affected by the N-induced fluctuations. To address these questions, we examined electron and hole transport in InGaAsN through resistivity, Hall mobility, photo-

conductivity, and solar cell photoresponse measurements. We have investigated carrier transport in MOCVD-grown InGaAsN ($\approx 2\%$ N). Samples described in this work were annealed at 650°C for 30 minutes. From solar cell studies, hole diffusion lengths were found to be $\approx 1\text{micron}$, and those for electrons were much smaller. Hall measurements were performed on a series of compensated InGaAsN samples. Both electrons and holes displayed doping-dependent Hall mobilities which were thermally activated in some cases; by contrast, carrier concentrations were only weakly temperature dependent. Overall, the Hall data were inconsistent with a random alloy-induced mobility-edge. Instead, the Hall and four-terminal resistivity data were characteristic of transport limited by large-scale (\gg carrier mean free path) material inhomogeneities, similar to behavior observed in large-grain polycrystalline semiconductors. Photoconductivity and photoluminescence revealed a broad distribution of sub-bandgap states in both n and p-type InGaAsN. Clearly, further studies of InGaAsN, grown under different conditions, are required before we can assign "intrinsic" transport properties and limitations to this intriguing material. Sandia is a multiprogram laboratory operated by Sandia Corporation for the U.S. Dept. of Energy under contract DE-AC04-94AL85000. Additional funding was provided by Air Force Research Laboratory and Lockheed Martin.

2:20 PM, T4 +

Incorporation of Nitrogen in Group III-Nitride-Arsenides Grown by MBE: Sylvia G. Spruytte¹; Christopher W. Coldren¹; Michael C. Larson²; James S. Harris¹; ¹Stanford University, Solid State and Photo. Lab., CISX, Via Ortega, Stanford, CA 94305 USA; ²Lawrence Livermore National Laboratory, P.O. Box 808, L-222, Livermore, CA 94551 USA

Group III-Nitride-Arsenides are promising materials for 1.3 μm and 1.55 μm opto-electronic devices grown on GaAs substrates. The nitrogen causes the bulk bandgap to decrease dramatically and the smaller lattice constant of GaN results in less strain in GaInNAs compared to InGaAs. However, the growth of such Nitride-Arsenides is complicated by the divergent properties of Nitrides and Arsenides and the difficulty of generating a reactive nitrogen source. Group III-Nitride-Arsenides were grown by elemental source MBE employing a nitrogen r.f. plasma cell. Using the emission spectrum of the plasma, we determined the plasma conditions that maximize the amount of atomic nitrogen versus molecular nitrogen. The most important observation in terms of yield and reproducibility compared to the AsP system is that the nitrogen concentration is inversely proportional to the group III growth rate showing that for our growth conditions all the supplied atomic nitrogen is incorporated. Phase segregation and N_2 formation can be avoided by lowering the growth temperature. SIMS measurements revealed that the impurity concentration (B, C, H, and O) in our films is below $10^{17}/\text{cm}^3$. The luminescence properties of GaNAs and GaInNAs deteriorate rapidly with increasing nitrogen concentration. To improve luminescence efficiency, both GaNAs and GaInNAs must be annealed. The increase in photoluminescence efficiency results from a decrease in non-radiative recombination centers. As the impurity concentration in our films is low, we have been investigating crystal defects associated with nitrogen incorporation. The relationship between nitrogen concentration in the film and lattice parameter of the film is not linear for nitrogen concentrations above 2.9 mole % GaN, indicating that some nitrogen is incorporated on other locations than the group V lattice sites. For films with these higher nitrogen concentrations, XPS indicates that the nitrogen exists in two configurations: a Gallium-Nitrogen bond and another type of nitrogen complex in which nitrogen is less strongly bonded to Gallium atoms. Annealing removes this nitrogen complex. Annealing also improves the crystal quality of GaNAs quantum wells and films. Annealing of GaNAs and InGaAsNAs not only results in the increase of luminescence efficiency but also shifts of the emission spectrum towards shorter wavelengths. SIMS measurements revealed that the blue shift is predominantly due to out-diffusion of nitrogen. TEM studies show that the GaInNAs quantum wells are sharp and dislocation free. By optimizing growth and anneal of the GaInNAs active regions emitting at 1.2-1.25 μm , we have demonstrated broad-area lasers with threshold current densities as low as 450A/cm² and VCSELs with threshold current densities of 3kA/cm² and efficiencies of 0.066W/A.

2:40 PM, T5 +

High-Quality GaNAs/GaInAs Superlattices Grown by Gas-Source MBE: Y. G. Hong¹; C. W. Tu¹; ¹University of California-San Diego, Depts. of Elect. and Comp. Eng., La Jolla, CA 92093-0407 USA

Recently, the quaternary $\text{Ga}_{1-x}\text{In}_x\text{As}_{1-y}\text{N}_y$ alloy system has attracted a great deal of attention due to its potential applications in next-generation ultra-high-efficiency multijunction solar cells as well as in optoelectronic devices for optical communications. A problem with GaInNAs is its low carrier mobility and short minority carrier lifetime due to alloy scattering and degradation of material quality with nitrogen incorporation. To minimize alloy scattering, we have investigated short-period superlattices of GaNAs/GaInAs as a digital alloy of GaInNAs. We report the growth and characterization of these short-period superlattices and their comparison with random alloy. The layers in the superlattices are strain-compensated, i.e., GaNAs is under tension and GaInAs is under compression. Thus, thick $\text{GaIn}_{0.08}\text{As}/\text{GaN}_{0.03}\text{As}$ superlattices can be grown lattice-matched to the GaAs substrate. High-resolution X-ray rocking curve for a typical sample (0.4 μm thick superlattice) shows clear satellite peaks, indicating that the digital alloys retain the composition modulation and close lattice match. Compared with dynamical simulations, the compositions can be determined. Short-period superlattices of GaNAs/GaInAs were grown by gas-source molecular beam epitaxy (GSMBE) using elemental Ga and In, thermally cracked arsine, and a RF plasma nitrogen radical beam source. Optimized growth temperature was investigated from 420° to 540°C. Several superlattices of $\text{GaN}_{0.03}\text{As}/\text{GaIn}_{0.08}\text{As}$ samples were grown with different period thicknesses from 16A to 100A. We also investigated the effect of rapid thermal annealing on the quality of digital alloys of GaInNAs. Since as-grown bulk and SL samples do not show photoluminescence (PL) at room temperature, we annealed the samples under the same condition, which was 700°C, 10 seconds in N_2 ambient. The PL intensity is improved by rapid thermal annealing. The PL intensity for digital alloys is 2.5 to 3 times higher than that of random alloys at room temperature, and the improvement is even greater at low temperature, by a factor of about 12. Optimized anneal temperature was investigated from 650°C to 900°C. High-temperature (above 850°C) anneal causes In and N interdiffusion and forms GaInNAs. Hall measurements on Sample #2726 (235-period superlattice $\text{GaN}_{0.03}\text{As}$ (8A)/ $\text{GaIn}_{0.08}\text{As}$ (8A)) and the reference sample (4000A $\text{GaIn}_{0.04}\text{N}_{0.015}\text{As}$) show that the electron mobility is improved by a factor of almost two (240 vs. 130 $\text{cm}^2/\text{V}\cdot\text{sec}$). These data show that the superlattice GaNAs/GaInAs digital alloy is very promising to improve the quality of quaternary GaInNAs random alloy.

3:00 PM Break

3:40 PM, T6

High Electron Mobility Transistor using GaInNAs Channel Grown by LP-MOVPE: Toshihide Kikkawa¹; Kozo Makiyama²; Takeshi Nishioka²; Hitoshi Tanaka²; ¹Fujitsu Laboratories Limited, Comp. Semiconduct. LSI's Lab. and ECE Dept., UCSD, 9500 Gilman Dr., La Jolla, CA 92093-0407 USA; ²Fujitsu Laboratories Limited, Comp. Semiconduct. LSI's Lab., 10-1 Morinosato Wakamaiya, Atugi, Kanagawa 243-0197 Japan

Since band gap energy of less than 1.0eV can be obtained using GaInNAs, many researchers have focused on long wavelength laser application. In this study, we studied the application for high electron mobility transistors (HEMTs) using GaInNAs channel. GaInNAs/GaAs has large conduction band offset. Thus, our objective is growing AlGaAs/InGaAs HEMT structures with high 2DEG concentration. We used reduced pressure barrel reactor capable of growing five 3-inch wafers per run. Growth temperatures were between 520-600°C. TEGa, TMIn, TMAI, DMH, AsH₃, and Si₂H₆ are used. V/III ratios of AlGaAs, InGaP and GaAs were 60, 400 and 5. Growth pressure was 50hPa. First, GaAs/GaInNAs-QW structure was grown. In mole fraction of GaInNAs was 0.15. Many researchers have observed H passivation into GaInNAs. We investigated in-situ annealing method as follows. 1) Conventional growth without any annealing. 2) T_g increased during growth interruption just after 2nm thick GaAs is grown on GaInNAs. 3) T_g increased just on the GaInNAs surface during growth interruption under N/As pressure. Using method #3), we could effectively reduce H concentration less than 1E18 cm⁻³ (detection limit). We also found that N-atoms are accumulated at the interface from GaAs to GaInNAs. We suppose that, at the beginning of GaInNAs growth, N-atoms are incorporated into GaAs, forming GaNAs. Because appropriate

growth temperature of GaInNAs used in this study is lower than that of GaNAs. When we grew GaNAs at a growth temperature of GaInNAs, N-atoms were drastically incorporated into GaNAs. To suppress this effect, we inserted 2nm-thick InGaAs between GaInNAs and GaAs. Then, we grew HEMT structures that consist of 35nm-AlGaAs electron supplying layer with doping concentration of 2e18 cm⁻³, 14nm-GaInNAs-channel layer, 2nm-InGaAs, and 600nm-GaAs buffer layer. We increased T_g at the interface from GaInNAs to AlGaAs under growth interruption. When InGaAs layer was not inserted at the interface, we could not measure 2DEG concentration by Hall measurements but observed p-type carrier accumulation at the interface using C-V measurement. We investigated the effect of substrate misorientation on 2DEG. N incorporation efficiency was larger at A-step than at B-step. However, when N concentration was the same, mobility for HEMT structures on substrates misoriented towards <111>B was larger than that towards <111>A. We obtained mobility of 1000-2000 cm^2/Vs with 2DEG concentration over 2-2.5e12 cm⁻². Low mobility is due to large effective mass of electron in GaInNAs. We fabricated HEMTs with 0.2um-gate. Transconductance of 250 mS/mm with V_{th} of -1.6V was obtained as the first fabrication. Large V_{th} value demonstrates large conduction band offset compared AlGaAs/GaAs HEMT. Although the mobility is low, the transconductance is not so low for such a large V_{th}, suggesting that saturation velocity is not quite low.

4:00 PM, T7

Exploring OMVPE-Grown InGaAsN for Electronic and Optoelectronic Devices: Nein-yi Li¹; Pablo Chang²; Albert Baca²; Jeff Laroche³; Fang Ren³; Eric Armour²; Jenifer Hills¹; Michelle Xie¹; Desmond Thang¹; Mark Stan¹; Paul Sharps¹; Charlie Wang⁴; Hong Hou¹; ¹Emcore Corporation, Emcore PhotoVoltaics, 10420 Research Rd. SE, Albuquerque, NM 87123 USA; ²Sandia National Laboratories, 1515 Eubank S. E., Albuquerque, NM 87185-0603 USA; ³University of Florida, Dept. of Chem. Eng., Gainesville, FL 32611 USA; ⁴Emcore Corporation, MODE, 5741 Midway Park Place, NE, Albuquerque, NM 87109 USA; ⁵Emcore Corporation, 394 Elizabeth Ave., Somerset, NJ 08873 USA

InGaAsN is a new material system that has received a lot of attention lately. Incorporating a small amount of N into InGaAs results in a reduction of its lattice constant, thus reducing the strain of InGaAs layer grown on GaAs. In addition, due to a large bandgap bowing, the E_g decreases as N is added, a desirable characteristic for GaAs-based device structures that require material with a smaller E_g than the 1.42 eV of GaAs. The InGaAsN material system may be an excellent alternative for low-power HBTs, high-efficiency solar cells and long-wavelength laser diodes. Therefore, in this study, we explore OMVPE-grown InGaAsN for application of electronic and optoelectronic devices. First, we present the first functional Pnp AlGaAs/InGaAsN/GaAs and Npn InGaP/InGaAsN/GaAs DHBTs lattice matched to GaAs. The Pnp InGaAsN DHBT has a peak current gain of 25, and a low V_{on} of 0.79 V which is ~0.25 V lower than in a comparable Pnp AlGaAs/GaAs HBT. The BV_{ceo} is 12 V, consistent with its GaAs collector thickness and doping level. For the Npn InGaP/InGaAsN/GaAs DHBT, it has a low V_{on} of 0.81 V, which is 0.13 V lower than in an InGaP/GaAs HBT. A peak current gain of 23 with nearly ideal I-V characteristics has been demonstrated. The ideality factor of I_b and I_c are 1.10 and 1.08, respectively, indicating high-quality InGaP/InGaAsN B-E and InGaAsN/GaAs B-C junctions. Since GaAs is used as the collector, BV_{ceo} is 10 V, consistent with the BV_{ceo} of InGaP/GaAs HBTs of comparable collector thickness and doping level. Secondly, we report another application of InGaAsN, with E_g of 1.25 eV, for high-efficiency solar cells. An inactive InGaP top cell (~6750Å thick) was grown on the top of N-on-p polarity InGaAsN cell as the filtering layer. Without an anti-reflection coating on the InGaAsN solar cell, a short-circuit current density of 11 mA/cm² and an open-circuit voltage of 0.75 Volt are obtained under simulated AM0 illumination. The internal quantum efficiency higher than 80% has also been achieved. Lastly, we describe optical characteristics of 1.27 um InGaAsN DH laser diodes with two InGaAsN/GaAs QWs. For a broad-area laser diode with the stripe width of 50 μm and the cavity length of 440 μm , a threshold current density of 1.3 KA/cm² and a peak power of 140 mW per facet have been demonstrated. All these results demonstrate the potential of InGaAsN as an alternative for various application not only in low-power electronic devices but also in high-performance optoelectronic devices. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

4:20 PM, T8 +

Ga(In)NP/GaP Grown by Gas-Source MBE and Its Application for Red Light-Emitting Diodes: *H. P. Xin*¹; *R. J. Welty*¹; *C. W. Tu*¹; ¹University of California-San Diego, Depts. of Elect. and Comp. Eng., La Jolla, CA 92093-0407 USA

Developing new materials and structures for efficient visible light-emitting diodes (LEDs) is of growing interest due to their wide applications, such as outdoor variable message signs and traffic lights. Recently extensive research has been done on the AlGaInP alloy system grown on GaAs substrates for high-brightness red LEDs. Some drawbacks, however, exist for these LEDs, such as poor current spreading and strong light absorption by the GaAs substrate. Many processes have to be used to solve these problems, including the growth of a thick GaP or AlGaAs "window" layer to improve current spreading, etching the GaAs substrate and wafer-bonding to a transparent GaP substrate to improve light-extraction efficiency. In this paper we investigate a not yet well studied material family of Ga(In)NP to explore their novel properties for red LED applications. Ga(In)NP samples were grown on (100) GaP substrates by gas-source MBE with a RF nitrogen radical beam source. Incorporation of N in GaN_xP_{1-x} alloys ($x \geq 0.43\%$) is found to lead to a direct bandgap behavior, which agrees well with theoretical predictions. A strong photoluminescence (PL) emission from GaNP bulk layers is observed at room-temperature for the first time. Incorporation of In to GaNP alloy to lattice-match to GaP decreases the PL energy and increases the integrated PL intensity by 40%. The PL peak, however, becomes broader probably due to increased composition fluctuations. From the PL peaks of a series of GaN_{0.025}P_{0.975}/GaP multiple quantum wells with different well thicknesses grown at the same growth condition, we determine the conduction band effective mass to be $m_c \sim 0.9m_e$ for the GaN_{0.025}P_{0.975} alloy. This indicates a mixing of Γ and X band wave functions in the conduction band. A red GaN_{0.011}P_{0.989}/GaP double-heterostructure (DH) LED directly grown on a GaP substrate was fabricated. This approach eliminates two process steps for high brightness AlGaInP LEDs: etching the GaAs substrate and wafer-bonding to a GaP substrate. It is also easier to grow a thick homoepitaxial GaP window on the GaP substrate to improve current spreading. The GaN_{0.011}P_{0.989}/GaP DH LEDs exhibit an emission around 650 nm, and 20 times stronger emission efficiency than that of GaN_{0.011}P_{0.989} pn homojunction LED. With further optimization of the growth conditions for Ga(In) NP active layer and using advanced structures, GaNP DH LEDs are expected to be a new generation of high-brightness LEDs.

4:40 PM, T9

Electronic Structure of Nitrogen Pairs in GaP and GaAs: *Paul Kent*¹; *Alex Zunger*¹; ¹National Renewable Energy Laboratory, Solid State Theory, 1617 Cole Blvd., Golden, CO 80401 USA

The early stages of formation of GaAsN and GaPN alloys involve the creation of nitrogen pairs inside the host. The many strong luminescence lines associated with these pairs have intrigued the scientific community for over a quarter of a century. However, it is now clear that the leading (Hopfield) model in the field fails to correctly associate the PL lines with simple, n-th neighbor nitrogen pairs. We have investigated the electronic and optoelectronic properties of the N-N pairs using a combination of large supercell empirical pseudopotential and self-consistent density functional calculations. The interaction of the nitrogen atoms results in an exceptionally rich series of gap levels that are compared with experimental photoluminescence measurements. Our calculations show that the conventional assignment and models of the observed luminescence lines, in terms of the n-th neighbor positions of the isoelectronic nitrogen defects, are inadequate to describe the role of nitrogen on the electronic structures of these III-V systems. Our calculations also demonstrate that a strong multiband coupling between conduction levels exists even for very low nitrogen concentrations (<0.1%), denoting an early onset of alloy formation. We explain our numerical results via a model that incorporates the major physical factors at play: (i) impurity-mediated electronic coupling of the L_{1c} , X_{1c} and Γ_{1c} conduction band edges, (ii) bonding-antibonding splitting due to the interaction of the two nitrogen atoms in a pair, and (iii) the structural relaxation of the different neighbor pairs. We will discuss differently oriented N-N pairs and pressure effects.

Session U. Properties of Quantum Wires and Wells, Wires, and Superlattices

Thursday PM Room: Lindsey Auditorium
June 22, 2000 Location: Sturm Hall

Session Chairs: Jim Merz, University of Notre Dame, Notre Dame, IN 46556 USA; Eric Jones, Sandia National Laboratory, Albuquerque, NM 87185-0601 USA

1:20 PM, U1

Anticorrelated Vertical Self-Organization of Stacked InAs Quantum Wires on InAlAs/InP(001): *Michel Gendry*¹; *Julien Brault*¹; *Genevieve Grenet*¹; *Guy Hollinger*¹; *Olivier Marty*²; *Michel Pitaval*²; *José Olivares*³; *Georges Bremond*³; *Taha Benyattou*³; *Catherine Priester*⁴; ¹Laboratoire d'Electronique-LEOM, 36 Ave. Guy de Collongue, Ecole Centrale de Lyon, Ecully 69131 France; ²Laboratoire d'Electronique-LENAC, Universite Lyon 1, Villeurbanne 69131 France; ³Laboratoire de Physique de la Matière-LPM, INSA de Lyon, Bat 502, Villeurbanne 69621 France; ⁴IEMN, Dept. ISEN, Villeneuve d'Ascq 59652 France

Self-formation of strained coherent islands using Stranski-Krastanov growth mode is a promising tool for the fabrication of nanostructures such as quantum wires and quantum dots. To stack layers of nanostructures is today a widely used approach to improve the nanostructure self-organization. We report here on the stacking process of InAs nanostructures grown on In_{0.52}Al_{0.48}As spacer layers lattice matched to an InP(001) substrate. This system is indeed very promising for quantum dot intraband infrared photodetectors (QDIP) and for quantum dot lasers. Using AFM imaging, TEM microscopy and photoluminescence, we show that i) a wire-like shape is strongly favoured by the stacking process (whatever was the shape of the foremost grown islands) and ii) the InAs wire widths and heights are depending on the spacer thickness (for spacer thickness in the 10-40nm range) with an improvement of the wire size homogeneity for spacer thickness in the 10-15nm range. Optical properties of stacked structures can thus be optimized and adapted (band gap shifting from 0.8eV to 0.86eV at 300K) by a judicious choice of the spacer thickness. Moreover, TEM images show off a surprising anticorrelated vertical wire alignment instead of the usual on-top vertical alignment. This arrangement is thought to be the result of the phase separation which is observed in the InAlAs spacer layers. This phase separation looks like indium-rich V-like features originating from each InAs wire and propagating evanescently within the InAlAs spacer layer. It is thought to be at the root of the experimentally observed wire anticorrelation because the meeting point of two V-like arms could be an adequate nucleation site for a subsequent InAs wire growth. Calculation of the alloy decomposition of the InAlAs spacer layers during their growth corroborates this hypothesis. The model shows how phase separation comes from a combination of mixing enthalpy, local strains (both of them derived from a Valence Force Field description using Keating's formalism) and growth front morphology effects.

1:40 PM, U2 +

Temperature Dependent Multi-Axial Strain Properties of Self-Assembled Quantum Wires: *David Eli Wohlert*¹; *Kuo-Lih Chang*¹; *Kuang-Chien Hsieh*¹; *Keh-Yung Cheng*¹; ¹University of Illinois, Microelect. Lab., 208 N. Wright St., Urbana, IL 61801 USA

Over the years, anomalies in the temperature behavior of the peak photoluminescence (PL) energy have been observed in many different materials. Alloys that are susceptible to phase separation or ordering such as InGaP, InGaIn, InGaAlAs, and InGaAsP have all shown deviations from the Varshni equation which describes the change in band gap with respect to temperature. However, the most striking departure from the temperature dependent behavior embodied by the Varshni equation is seen in self-assembled GaInAs quantum wires (QWRs) formed by the strain-induced lateral-layer ordering process. Peak PL wavelength stability over large temperature ranges is common behavior in these struc-

tures. Typically, potential localization or crystal defects have been used to explain the band gap anomalies for bulk materials. But the self-assembled GaInAs QWRs studied here possess a multi-axial strain, which is not seen in the materials mentioned above. Many of these GaInAs QWR samples that demonstrate interesting band gap behavior below 300K, continue to show unexpected results above room temperature. Stability in peak PL wavelength is often observed up to 380K. But some samples will show a blue-shift or red-shift in peak PL wavelength when the temperature changes from 300 to 380K. Because a temperature stable band gap above room temperature could be useful in various laser diodes, GaInAs QWR samples with slightly different structures and growth conditions were studied so as to determine what design is the most conducive to a stable band gap above room temperature. It was found that the most important design variable was the growth interrupt scheme used during the deposition of the self-assembled QWRs. To investigate the source of the band gap anomalies with respect to temperature, we have done an extensive study of the polarized PL (PPL) spectra of self-assembled GaInAs QWRs. The PPL results indicate a crossing in the light-hole (LH)-heavy-hole (HH) bands as the sample temperature varies between 77 and 300K. Moreover, this LH-HH crossing is only observed in GaInAs QWRs that display the anomalous band gap behavior with respect to temperature. This band-crossing phenomenon serves as evidence that the multi-axial strain in the GaInAs QWRs is itself a function of temperature, which ultimately gives rise to the band gap anomalies with respect to temperature.

2:00 PM, U3 +

Micro-Photoluminescence Spectroscopy of Single (Al, Ga)As Quantum Wire Grown on Vicinal (110) Surfaces: *Takeshi Ota*¹; *Kenzo Maehashi*¹; *Kenichi Oto*²; *Kazuo Murase*²; *Hisao Nakashima*¹; ¹Osaka University, The Instit. of Sci. and Indust. Rsch., 8-1 Mihogaoka Ibaraki, Osaka 567-0047 Japan; ²Osaka University, Dept. of Phys. Fac. of Sci., 1-1 Machikaneyama Toyonaka, Osaka 560-0043 Japan

The investigation of single quantum wire has been highly requested for viewpoint of fundamental physics as well as for application to devices. Using GaAs and AlGaAs quantum wires, we have performed single quantum wire spectroscopy and unique features of these quantum wires have been observed by micro-photoluminescence. The GaAs and AlGaAs quantum wires have been naturally formed on vicinal GaAs(110) surfaces with giant steps by molecular beam epitaxy. The formations of the GaAs and the AlGaAs quantum wires are induced by thickness modulation of GaAs layer and compositional modulation of AlGaAs layer at the giant step edges, respectively. In order to observe isolate quantum wires, Al masks with sub-micron sized apertures, which were fabricated by electron-beam lithography and lift-off technique, have been deposited on the sample surfaces. The micro-photoluminescence spectrum at 4K from single GaAs quantum wires, which is observed through 0.2 μm apertures, shows that the GaAs quantum wire consists of a number of anomalously sharp peaks, having a full width at half maximum (FWHM) of several hundreds eV. The activation energy of these sharp peaks is estimated to be a few meV from temperature dependent measurements. Therefore, the sharp peaks are considered to originate from excitons captured in local potential minima due to interface fluctuations of the GaAs quantum wires with 3 nm thickness. In contrast, the characteristic features of the micro-photoluminescence spectrum from the single AlGaAs quantum wires are quite different from those of the GaAs quantum wires. The micro-photoluminescence spectrum from single AlGaAs quantum wires through 0.2 μm apertures exhibits one peak with low energy tail and sharp high energy Fermi edge (a FWHM of 1 meV) and a number of the sharp peaks are not observed. Since the AlGaAs quantum wires are very thick (10 nm), the interface fluctuation is observed as the low energy tail. The AlGaAs wires show a clear one-dimensional feature in comparison with the GaAs wires. The monochromatic cathodoluminescence images clearly visualize one-dimensional luminescence from single AlGaAs quantum wires. On the other hand, several numbers of the bright spots are observed in the GaAs quantum wire. The results of the cathodoluminescence images agree quite well with those of the micro-photoluminescence.

2:20 PM, U4

High Resolution X-Ray Diffraction from InGaAs/GaAs Quantum Dot Superlattice Structures: *Debdas Pal*¹; *Dong Pan*¹; *Elias Towle*¹; ¹University of Virginia, Dept. of Elect. Eng., Lab. for Optics and Quant. Elect., Thornton Hall, Charlottesville, VA 22903 USA

There is now considerable interest in semiconductor quantum dots for their fundamental properties as well as potential applications in electronic and opto-electronic devices. The knowledge of structural parameters of quantum dots is essential to develop high performance quantum dot devices. The high resolution X-ray diffraction technique has been used successfully to study strained quantum well structures where the structural parameters, such as alloy composition and thickness, can be determined accurately. However, the effective measurement technique has not been widely applied for self-formed quantum dot structures^{1,2}. We have studied high resolution X-ray diffraction on good quality, high density Molecular Beam Epitaxy (MBE) grown InGaAs/GaAs quantum dot superlattices where a large number of satellite peaks upto 23 were observed. The In_{0.3}Ga_{0.7}As/GaAs, 5 period quantum dot superlattice structures were grown by MBE at 500°C on (001) GaAs. The dot height, lateral extent and density were found to be 6nm, 20nm and $7 \times 10^{10} \text{cm}^{-2}$, respectively from the Atomic Force Microscopy images. The FWHM of the photoluminescence spectrum at 78K was found to be 25meV; which indicates the good quality of the quantum dots. High resolution X-ray diffraction measurements were performed using double crystal Phillips Materials Research Diffractometer. Rocking curves were recorded at the vicinity of (004), (224) and (113) reflections. The peak of the highest intensity at 0° in the rocking curve for (004) reflection is due to the GaAs substrate. The strong asymmetry in the satellite peaks that shifts left side indicates a compressive strain in the structure. We would like to point out that a large number of satellites up to 23 are observed in the rocking curve. The pendellösung fringes can also be found between the satellites. Similar rocking curves with many satellite peaks have been reproducibly observed from our other quantum dot superlattice structures. We simulated the rocking curves assuming a quantum well including wetting layer at the interface. The simulations were performed based on the solution of Takagi Taupin's equation in the Dynamical diffraction theory. The better agreement between the experimental and calculated curves was observed using lower indium composition of 23% in InGaAs of thickness (7.8nm) which is much larger than that of the wetting layer. The same parameters were used to obtain better agreement between the experimental and calculated curves for (113) and (224) reflections. We will discuss all the results later.

2:40 PM, U5

Spin Lifetimes in III-V Heterostructures: *Wayne H. Lau*¹; *Jonathon T. Olesberg*¹; *Michael E. Flatte*¹; ¹University of Iowa, Dept. Phys. and Astro., 100 IATL, Iowa City, IA 52242 USA

Potential applications of coherent spin states in quantum wells have led to new ultrafast optical studies of electron spin dynamics in these structures. A critical requirement of any spin technology is the ability to control the spin states and substantially extend the electron spin lifetime in these systems. Consequently, a full understanding of the spin relaxation mechanisms is desirable. Electron spin relaxation in (001)-grown zincblende type semiconductors at room temperature is dominated by the precessional D'yakonov-Perel' (DP) [Sov. Phys. Solid State 13, 3023 (1972)] mechanism, which is a direct result of the spin splitting of the conduction band. Recently experimental spin lifetimes [Terauchi, et al., Jpn. J. Appl. Phys. 38, 2549 (1999)] in n-doped 7.5nm GaAs quantum wells at room temperature were found to be one order of magnitude longer than predicted for zincblende quantum-wells by D'yakonov and Kachorovskii (DK) [Sov. Phys. Semicond. 20, 110 (1986)]. A disparity of this degree requires further improvement of the DK theory to satisfactorily explain the electron spin relaxation in GaAs/AlGaAs quantum wells. We calculated the electron spin lifetimes in (001)-grown zincblende quantum wells employing a heterostructure model based on a restricted basis set of fourteen bulk bands. This fourteen-band model accounts for the inversion asymmetry of the zincblende lattice nonperturbatively. Our predicted spin lifetimes agree with the measured values within a factor of two. We have also calculated the spin splitting and spin lifetimes in InGaAs/InP quantum wells with 10nm barriers and wells ranging from 4 to 10nm. We find the spin splitting due to the native interface asymmetry (NIA) of this non-common-atom interface dominates for a 4nm quantum well over the bulk inversion asymmetry (BIA) of the zincblende lattice, but the BIA contribution is dominant for a 7nm and 10nm quantum well. The theoretical spin relaxation lifetime is again within a factor of two of the experimental value [Tacheuchi, et al., Appl. Phys. Lett. 70, 1131 (1997)].

3:00 PM Break

3:40 PM, U6 +

Absorption and Photoluminescence Characteristics of MgZnO/ZnO Quantum Wells: Chia-Wei Teng¹; John F. Muth¹; Robert M. Kolbas¹; A. K. Sharma²; C. Jin²; A. Kvit²; J. Narayan²; ¹NC State University, Elect. and Comp. Eng. Depts., 232 Daniels Hall, P.O. Box 7911, Raleigh, NC 27695-7911 USA; ²NC State University, Matls. Sci. and Eng. Depts., P.O. Box 7916, Raleigh, NC 27695-7916 USA

ZnO has a wurtzite crystal structure and a band gap about 3.37 eV at room temperature. Alloying ZnO films with MgO permits a tunable band gap between 3.3 eV to 4 eV. This facilitates the band gap engineering for MgZnO/ZnO heterostructures. ZnO has a large exciton binding energy of ~60 meV, which results in extremely efficient emission with room temperature lasing reported in thin films and microcrystallites. This excitonic nature of the emission processes in ZnO and its alloys can be enhanced by fabricating MgZnO/ZnO quantum well structures due to two dimensional quantum confinement. Mg_xZn_{1-x}O/ZnO (x~0.27) multi-quantum well (MQW) structures were fabricated on sapphire (0001) substrates by pulsed laser deposition using a KrF excimer laser in a high vacuum chamber. Clearly defined interfaces between wells and barriers were observed by cross-sectional transmission electron microscopy. Optical transmission measurements were taken on a dual beam Cary 5E ultraviolet-visible near-infrared (UV-VIS-NIR) spectrophotometer at room temperature and liquid nitrogen temperature. Photoluminescence (PL) spectra were excited with a continuous wave argon-ion laser (270-305 nm) and collected using a 0.64 m spectrometer equipped with an S-20 photocathode. The two dimensional A- and B-exciton absorption (367 nm and 360 nm) were clearly resolved at 77K. A finite square well model was used to calculate the confined energy states in the quantum well. The exciton binding energies in the quantum well were measured to be about twice the values in the bulk ZnO. The intense ultraviolet photoluminescence at room temperature and 77K were measured. The blue shift of the measured PL and absorption peak energies relative to the band edge of the bulk ZnO films was attributed to quantum confinement effects. The observation that the PL peak positions coincide with the exciton absorption peaks indicates the emission resulted from quantum-confined exciton recombination processes. The mechanism is different from bulk ZnO where the emission process was due to free exciton recombination assisted by an LO-phonon. These results indicate that MgZnO/ZnO MQWs are a promising device structure for efficient ultraviolet light emitting devices.

4:00 PM, U7 +

Si-Modulation Doped In_xGa_{1-x}As/In_{0.52}Al_{0.48}As Pseudomorphic Quantum Wells Grown on (411)A InP Substrates by MBE: Issei Watanabe¹; Takahiro Kitada¹; Satoshi Shimomura¹; Satoshi Hiyamizu¹; ¹Osaka University, Grad. Sch. of Eng. Sci., 1-3 Machikaneyama, Toyonaka, Osaka 560-8531 Japan

Heterostructures with atomically flat heterointerfaces over a full device size are necessary for achieving ultra-high performance of quantum devices such as high electron mobility transistors (HEMTs). We have reported that effectively atomically flat interfaces over a macroscopic area (> 1 cm²) (“the (411)A super-flat interfaces”) can be formed not only in In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As quantum wells (QWs) lattice-matched to (411)A InP substrates but also in In_{0.72}Ga_{0.28}As/In_{0.52}Al_{0.48}As pseudomorphic QWs grown on (411)A InP substrates grown by molecular beam epitaxy (MBE). Recently, this result was applied to pseudomorphic (411)A In_{0.7}Ga_{0.3}As/In_{0.52}Al_{0.48}As QW-HEMT structure with a spacer width (L_{sp}) of 7 nm and a well width (L_w) of 14 nm, we obtained higher electron mobility than (100) QW-HEMTs with same structure. In this paper, we investigated electron mobility of 2DEG in (411)A In_xGa_{1-x}As/In_{0.52}Al_{0.48}As QW-HEMT structures on InP substrates as a function of Indium content (x) of InGaAs channel layer. The width of a spacer and a well were 7-nm-thick and 10-nm-thick respectively. Increase of Indium content of InGaAs channel layer leads to decrease effective mass of electron and increase conduction band offset of InGaAs/InAlAs conduction band. As a results, we obtained that the highest electron mobility $\mu = 56000$ cm²/Vs with sheet carrier density $N_s = 3.5 \times 10^{12}$ cm⁻² at 77K and $\mu = 11000$ cm²/Vs with $N_s = 3.7 \times 10^{12}$ cm⁻² at 300K in (411)A QW-HEMT (x=0.74). The (411)A In_xGa_{1-x}As/In_{0.52}Al_{0.48}As QW-HEMTs consist of a 5-nm In_{0.53}Ga_{0.47}As (at 520°C), 3-minute growth interruption for rising of substrate temperature from 520°C to 540°C, 20-nm In_{0.53}Ga_{0.47}As and 300-nm In_{0.52}Al_{0.48}As buffer

layers, an In_xGa_{1-x}As channel (L_w=10 nm, x=0.70-0.82), undoped In_{0.52}Al_{0.48}As barrier (L_{sp}=7 nm), a Si-delta doping (1x10¹³ cm⁻² nominal), a 20-nm undoped In_{0.52}Al_{0.48}As, and finally, a 40-nm Si-doped In_{0.53}Ga_{0.47}As cap layer for ohmic contacts. The (411)A QW-HEMTs were grown at Ts of 540°C under V/III pressure ratio [As₄/(In+Ga)] of 8. Growth rates of In_{0.53}Ga_{0.47}As and In_{0.52}Al_{0.48}As were 1 μm/h and 1.02 μm/h respectively. These growth conditions for (411)A InP were optimized in InGaAs/InAlAs QWs before. With increase of Indium content of InGaAs channel layer, electron mobility of the (411)A QW-HEMTs (77K) rises from 48000 cm²/Vs with x=0.70 and it reaches a peak of 56000 cm²/Vs with x=0.74. At last, it falls to 45000 cm²/Vs with x=0.82. It is caused by critical thickness of InGaAs channel layer. The electron mobility of 56000 cm²/Vs of the (411)A QW-HEMT with x=0.74 is the highest of that of QW-HEMTs with same sheet carrier density.

4:20 PM, U8 +

Preparation and Properties of AlGaIn/GaN Superlattices: Uttiya Chowdhury¹; Damien J. H. Lambert¹; Michael M. Wong¹; Ho Ki Kwon¹; Leah Bergman²; Mitra Dutta³; Michael A. Strosio³; Serguei M. Komirenko⁴; Ki Wook Kim⁴; Robert J. Nemanich⁵; Zuzanna Liliental Weber⁵; Russell D. Dupuis¹; ¹The University of Texas at Austin, Microelect. Rsch. Ctr., PRC/MER-R9900, Austin, TX 78712-1100 USA; ²North Carolina State University, Dept. of Phys., Raleigh, NC 27695-8202 USA; ³US Army Research Office, P.O. Box 12211, Research Triangle Park, NC 27709-2211 USA; ⁴North Carolina State University, Dept. of Elect. and Comp. Eng., Raleigh, NC 27695-8202 USA; ⁵Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720 USA

We report the growth of high-quality AlGaIn/GaN and AlN/GaN superlattices (SLs) by low-pressure metalorganic chemical vapor deposition (MOCVD). The heteroepitaxial wafers are grown in an EMCORE D125 UTM reactor with adduct-purified trimethylgallium and trimethylaluminum, and purified ammonia as precursors. The epitaxial structures are grown in H₂ at pressures ~100 Torr on (0001) sapphire substrates. A two-step growth procedure was used and the high-temperature growth was carried out at 1050-1070°C. Superlattices with a variety of periods and individual layer compositions and thicknesses were grown varying from GaN(10nm)/AlN(10nm) to GaN(1nm)/Al_{0.2}Ga_{0.8}N(3.3nm). We have varied the growth conditions and have studied the correlation of the growth procedure with the symmetric and asymmetric X-ray diffraction spectra, surface morphology, secondary ion mass spectroscopy (SIMS) profiles, and photoluminescence (PL) and cathodoluminescence (CL) spectra. The effect of the growth conditions and the SL structure upon the RMS roughness of the surface and the asymmetric X-ray rocking curve FWHM values was explored. The X-ray diffraction data and transmission electron microscopy analysis has verified the presence of a superlattice in these samples. TEM images show abrupt interfaces but it is difficult to evaluate the compositional fluctuations that may be present. The optical properties of the SLs were studied using variable-temperature PL and time-resolved PL (TRPL) as well as 4K and 300K CL. The PL spectra show strong emission at wavelengths characteristic of the two-dimensional nature of the carrier confinement in the superlattice. In order to gain further insight into the mechanisms determining the recombination dynamics of the superlattice, the PL intensity as a function of temperature, I(T), was investigated for several SL samples. The temperature dependence of the PL emission of the GaN/Al_{0.2}Ga_{0.8}N superlattice sample does not follow the monotonic variation to lower energies with increasing temperature expected for the band-edge shift. Similar behavior has previously been observed in quantum-well structures of AlGaIn/InGaIn/GaN, InGaAs-InP, and GaInAs/AlInAs, as well as in superlattices of ZnSe/MgS, and GaAs/AlAs. This anomalous temperature dependence has been attributed to the contribution of an extrinsic density of states, resulting from a degree of disorder occurring mainly at the layer interfaces, which may be of compositional and/or structural in origin. Our analysis of the PL emission verifies the existence of such a defect-related density of states, involved in the recombination of excitons at low temperatures. We also find that at higher temperatures, the density of states acts as a non-radiative channel for the luminescence. We also observe a shift of the phonon energies in the SL emission. The higher value of the average energy of the phonons involved in the superlattice scattering is consistent with the predictions for the phonon modes of GaN/AlGaIn heterolayers.

4:40 PM, U9

Time-Resolved Photoluminescence Studies of Al_xGa_{1-x}N/GaN Heterostructures Grown by MOCVD: *Ho Ki Kwon*¹; Christopher J. Eiting²; Damien J. H. Lambert¹; Michael M. Wong¹; Russell D. Dupuis¹; ¹The University of Texas at Austin, Microelect. Rsch. Ctr., PRC/MER-R9900, Austin, TX 78712-1100 USA; ²Air Force Research Laboratory, Manufact. and Matls. Direct., WPAFB, OH 45433-7707 USA

We have studied the time-resolved photoluminescence (TRPL) of the GaN donor-bound-exciton (DX) in GaN heteroepitaxial layers and Al_xGa_{1-x}N/GaN single heterostructures (SHs) grown on sapphire by metalorganic chemical vapor deposition (MOCVD). The SHs consist of ~30 nm of undoped AlGa_N grown on 2 mm undoped GaN layers. The PL and TRPL have been measured at temperatures varying from 300K to 4K. The 4K photoluminescence (PL) of the SHs exhibits two peaks, a high-energy peak due to free-exciton recombination in the "bulk" GaN region, and a luminescence peak below the energy of the DX transition of the undoped GaN layer. This lower-energy peak is attributed to radiative recombination of the two-dimensional electrons at the heterointerface with holes in the flat-band region. For TRPL measurements, the excitation source is a frequency-tripled Ti:Sapphire laser. The photon energy of this source is chosen to be lower than the bandgap energy of top AlGa_N layer. The luminescence is detected by microchannel-plate photomultiplier and processed using time-correlated single photon counting. To analyze the photoluminescence decay time constants, deconvolution techniques are used. At "normal" excitation intensities (average power, $I_{ex} \sim 4.4 \text{ mW/cm}^2$), the PL emission of the DX transition in undoped GaN decays in a few nanosecond and can be fitted using single exponential function with the time constant of 60 ps. The TRPL data from the AlGa_N/GaN SHs is somewhat different. The DX transition of undoped GaN in AlGa_N/GaN SHs decays in several nanoseconds. It can be fitted assuming two exponential functions with the time constants of 60 and 670 ps. By varying the excitation intensity, we have found that the decay time of the low-intensity part of the TRPL increases as the excitation intensity is reduced. This phenomenon is not observed in our undoped single layers of GaN/sapphire. Three exponential functions are needed to fit the SH TRPL results at low excitation levels under 0.3% of I_{ex} , and the time constants are much longer, e.g., for one sample, they are calculated to be 0.6 ps, 1.4 ns, and 36.7 ns. These are the longest values reported to date for III-N structures. Similar long time decay curves are also measured from the two-dimensional electron gas related luminescence peak. A mechanism to explain the observed PL decay in AlGa_N/GaN SHs is described. We propose that the initial "shorter" time decay is due to the radiative recombination of EHPs created by the pump laser in the "flat-band" region of the SH. The luminescence with the "longer" decay times is due to the re-absorption of photons generated by the recombination of electrons in the 2DEG with holes in the flat-band region. These photons interact with the electrons in the 2DEG, creating excited electrons that then relax back to the conduction band edge in the flat-band region and ultimately recombine.

5:00 PM, U10 +

Characterization of InGa_N/Ga_N Multiple Quantum Well LEDs Using Surface Photovoltage Spectroscopy, Photorefectance, and Contactless Electroreflectance: *B. Mishori*¹; M. Munoz¹; Fred H. Pollak¹; C. Tran²; I. Ferguson²; ¹Brooklyn College of CUNY, Phys. Dept. and NY State Ctr. for Adv. Tech. in Ultrafast Photo. Matls. and Appls., Brooklyn, NY 11210 USA; ²EMCORE Corporation, 394 Elizabeth Ave., Somerset, NJ 08873 USA

InGa_N/Ga_N multiple quantum well (MQW) structures have recently been the subject of considerable interest due to their application for blue-green light emitting (LED) and laser diodes. Using the nondestructive techniques of surface photovoltage spectroscopy (SPS), photorefectance (PR), and contactless electroreflectance (CER) we have characterized a number of important properties of two InGa_N/Ga_N LEDs with activated (sample #1)/unactivated (sample #2) p-doping in the top Ga_N cap layer. The SPS spectra yield important information about these p-doping levels. The PR/CER data exhibited contributions from both the MQW region and top p-GaN section. The samples consisted of 10 periods of 22 Å thick In_{0.22}Ga_{0.78}N QWs with 100 Å Ga_N barriers sandwiched between 4 μm thick buffer n-GaN:Si ($3 \times 10^{18} \text{ cm}^{-3}$) layer and a 3000 Å thick p-GaN layer ($3 \times 10^{17} \text{ cm}^{-3}$ for sample #1). A 500 Å p-Al_{0.10}Ga_{0.90}N ($3 \times 10^{17} \text{ cm}^{-3}$) region was placed between the active region and p-cap layer. To enhance light emission the MQWs were fabricated with considerable In alloy fluctua-

tions. In SPS the contact potential difference between the sample and a reference electrode is measured as a function of incident photon energy in a capacitive manner; these investigations used a Kelvin probe system. The SPS signals from these two samples have completely different lineshapes. The SPS spectrum from sample #1 contained contributions from two electric fields: the first one being distributed through the MQW region, AlGa_N layer, and space charge region (SCR) at the AlGa_N/p-GaN cap interface while the second is related to the surface SCR of the cap layer. The SPS data from sample #2 displayed a contribution only from surface SCR of the cap layer. A numerical simulation showed that for sample #1 the high p-doping of the Ga_N cap layer screens the surface charge which increases the electric field at the MQW region/p-GaN cap layer interface thus enhancing the SPS signal from this section of the structure. By comparison of the SPS data with the simulation the p-doping level can be determined to within 20%. The PR/CER spectra from the MQW region of the two samples contained features of the fundamental conduction to heavy-hole exciton transition (1C-1H) at energies of 2.907 eV (sample #1) and 2.956 eV (sample #2). This 49 meV red shift is a result of the quantum confined Stark effect in the former material. This observation confirms the electric field increase in the MQW of sample #1 due to the enhanced p-doping level. The broad linewidths (γ 60-70 meV) of the 1C-1H transition in both samples are due to the intentional In composition fluctuations in the MQWs. The Ga_N related signal from sample #1 is redshifted by about 60 meV in relation to sample #2. This difference is probably due to about 2% In interdiffusion from the MQW region.

Session V. Point and Extended Defects in Mismatched Materials

Thursday PM
June 22, 2000

Room: Sturm Auditorium
Location: Sturm Hall

Session Chairs: Jean Lee, Purdue University, Sch. of Matls. Sci. and Eng., West Lafayette, IN 47907 USA; Gene Fitzgerald, MIT, Depts. of Matls. Sci. and Eng., Cambridge, MA 02139 USA

1:20 PM, V1 +

Dislocation Glide, Blocking, and Reduction Kinetics in Compositionally Graded SiGe/Si: *Christopher W. Leitz*¹; Matthew T. Currie¹; Andrew Y. Kim¹; Mayank T. Bulsara²; Jessica Lai¹; Elissa M. Robbins¹; Eugene A. Fitzgerald¹; ¹Massachusetts Institute of Technology, Dept. of Matls. Sci. and Eng., 77 Massachusetts Ave., Rm. 13-4150, Cambridge, MA 02139 USA; ²Amberwave Systems Corporation, 165-U New Boston St., Ste. 279, Woburn, MA 01801 USA

High quality relaxed SiGe/Si is an important materials system for high speed FETs and monolithic integration of optoelectronics onto silicon substrates. In this study, the effects of growth temperature, substrate offset, and process conditions on threading dislocation density (TDD) in compositionally graded SiGe buffers are presented. To investigate dislocation glide kinetics in these structures, a series of identical samples graded to 30% Ge were grown at temperatures between 650°C and 900°C on (001)-, (001) offset 6° towards an in-plane <110>-, and (001) offset 6° towards an in-plane <100>-oriented Si substrates. Samples were characterized by etch-pit density, Nomarski optical microscopy, transmission electron microscopy, triple-axis x-ray diffraction, and atomic force microscopy. The field TDD in the on-axis samples varied exponentially with temperature, from $3.7 \times 10^6 \text{ cm}^{-2}$ at 650°C to $9.3 \times 10^4 \text{ cm}^{-2}$ at 900°C. The activation energy for dislocation glide in this series, calculated from the evolution of field TDD with growth temperature, was 1.38 eV, much lower than the expected value for this composition. This apparent deviation results primarily from the temperature dependence of dislocation pile-up formation and the rise in field TDD associated with this process. The TDD of samples grown on offset substrates exhibited a more complicated temperature dependence, likely because films grown

on offset substrates have a reduced tendency towards dislocation pile-up formation at low temperature and an increased tendency towards saturation in dislocation reduction reactions at high temperature. The effects of heterogeneous nucleation in our hot-wall ultrahigh vacuum chemical vapor deposition growth system were also studied in identical structures graded to 60% Ge in both heavily and lightly coated growth chambers. Samples grown in a heavily coated quartz tube had an overall TDD of $1.98 \times 10^6 \text{ cm}^{-2}$ and a field TDD of $1.31 \times 10^6 \text{ cm}^{-2}$. By contrast, samples grown in a nearly clean quartz tube had an overall TDD of $5.65 \times 10^5 \text{ cm}^{-2}$ and a field TDD of $4.23 \times 10^5 \text{ cm}^{-2}$. These results indicate the importance of process conditions in determining film quality. Finally, dislocation reduction processes were explored by initiating compositional grading to 15% Ge at 650°C and continuing the grade to 30% Ge at 900°C. The low-temperature portion of this growth provided an excess concentration of threading dislocations which could subsequently be annihilated during the high-temperature portion of the growth. Using this method, we attained a TDD between that obtained by compositional grading to 30% Ge exclusively at 650°C and exclusively at 900°C, allowing us to directly calculate dislocation reduction rates. Based on these results, we now have a predictive model for TDD in compositionally graded SiGe/Si over a wide range of growth conditions.

1:40 PM, V2 +

The Role of Substrate Orientation on Misfit Dislocation Interactions: *Petra Feichtinger*¹; Benjamin Poust¹; Mark S. Goorsky¹; Dwan Oster²; Tom D'Silva²; Jim Moreland¹; ¹University of California at Los Angeles, Dept. Matls. Sci. and Eng., 2521 Boelter Hall, Los Angeles, CA 90095-1595 USA; ²Wacker Siltronic Corporation, 7200 NW Front Ave., Portland, OR 97210 USA

Substrates with a high degree of off-orientation are often used with mismatched layers. In this study, the interactions between misfit dislocations at strained layer and substrate interfaces were examined to understand how interaction of extended defects in mismatched layers grown on off-oriented substrates differs from the interactions that are observed for layers grown using on-axis substrates. Misfit dislocations with opposite tilt components (which are parallel for a structure grown on an on-axis substrate) are inclined by opposite angles with respect to the $\langle 110 \rangle$ when the structure is grown on an off-oriented substrate. We determined that these non-orthogonal misfit segments could act to block each other and to cause cross-slip of those segments and change their relaxation direction. This can be shown to lead to localized preferential tilt of the lattice due to certain sets of interactions in one area of the wafer, while other areas show an opposite tilt due to other sets of dislocation interactions. Nominally (001) silicon epitaxial layers were deposited on highly doped p-type ($2.6 \times 10^{19} \text{ cm}^{-3}$) silicon substrates. This system has a mismatch of about 2×10^{-4} ; and at this low level of mismatch, mimics the early stages of relaxation in both graded buffer layers and in strained single layers. Substrate orientations of zero, 2.3, and 4.6° were used with the off-orientation direction along either a $\langle 110 \rangle$ or $\langle 100 \rangle$ direction. Layers were grown at different thicknesses and the as-grown wafers were also subjected to rapid thermal annealing to separate the influences of temperature and the stress acting on the dislocations. Double crystal x-ray topography is sensitive to the tilt and screw components of the different misfit segments and clearly delineates their interactions across the entire 150 mm wafer. The statistical advantage of examining dislocation interactions across an entire wafer confirmed that an excess of a certain type of dislocations (i.e., with the same Burgers vector) in one region does not necessarily represent the status of the dislocation distribution in other regions. This demonstrates why recent models proposed for the formation of tilt in partially relaxed layers that are based on measurements that use small sampling areas (such as TEM or single spot XRD measurements) are inconsistent with this and other experiments [F. Romanato, et al., J. Appl. Phys. 86 4748 (1999)] that show variation in the tilt distribution at different locations.

2:00 PM, V3 +

Low-Temperature GaAs Films Grown on Ge and Ge/GeSi/Si Substrates: *Carrie L. Andre*¹; John Boeckl¹; Steve A. Ringel¹; Robert N. Sacks¹; David M. Wilt²; Eugene A. Fitzgerald³; ¹The Ohio State University, Elect. Eng. Dept., 205 Dreese Labs., 2015 Neil Ave., Columbus, OH 43201 USA; ²NASA Glenn Research Center, Photovoltaic and Space Environ. Brnch., 21000 Brookpark Rd., MS 302-1, Cleveland, OH 44135 USA; ³Massachusetts Institute of Technology, Matls. Sci. and Eng. Dept., #13-4035, 77 Massachusetts Ave., Cambridge, MA 02139 USA

Low-temperature GaAs has received considerable attention due to its unique optical and electrical properties, and it has consequently been used in high-speed optoelectronics, photonics, and FET device structures. In addition to the possible realization of electrical isolation layers between Si and III-V devices afforded by LT-GaAs, the growth of this material in conjunction with conventionally grown III-V compounds on Si substrates could provide a more complete hierarchy of III-V devices integrated onto Si. Recently, compositionally graded GeSi layers on Si have been used as substrates for III-V growth and have hence become a viable solution for III-V/Si integration. While LT-GaAs has been previously grown directly on Si wafers, little is understood about the influence of lattice mismatch, substrate morphology, and heterovalent interfaces on the properties of LT-GaAs. Such issues must be addressed if LT-GaAs devices on Si substrates are to become a reality. Therefore, the present study considers the growth and properties of LT-GaAs on Ge wafers, first as a means to understand LT-GaAs growth on a low-mismatched, heterovalent interface, and second as a means to transfer LT-GaAs growth onto Ge-capped graded GeSi/Si substrates. LT-GaAs was grown by solid source molecular beam epitaxy at a substrate temperature of 320°C. For an accurate comparison, LT films were grown on GaAs and Ge substrates simultaneously by mounting multiple samples to a molybdenum block. These growth conditions produced a nominal as-grown lattice expansion of 0.07% on GaAs substrates, as measured by high resolution x-ray diffraction via reciprocal space mapping (RSM). LT-GaAs grown on Ge substrates showed an additional lattice expansion of ~0.007% when compared to growths on GaAs. This increase may result from the slightly larger lattice constant of Ge compared to GaAs, a 0.08% mismatch. LT-GaAs growth on Ge over a 100°C temperature range (300°C to 400°C) resulted in a monotonic decrease in lattice expansion, which was similar to that of LT-GaAs grown on GaAs. LT-GaAs/Ge samples were then annealed in-situ for 1 hr at 600°C and the formation of As precipitates in these layers was confirmed by transmission electron microscopy (TEM). From this it was concluded that LT-GaAs layers grown on Ge behave much like those grown on GaAs. LT-GaAs has subsequently been grown on Ge/GeSi/Si substrates to assess the impact of the graded buffer's cross-hatch morphology. Comparisons of LT-GaAs on the three types of substrates will include analysis of both structural and interface properties of these films as reported by RSM, secondary ion mass spectroscopy (SIMS), and TEM.

2:20 PM, V4 +

Evolution of Structural and Electronic Properties of Highly Mismatched InSb Films: *X. Weng*¹; D. L. Partin²; J. P. Heremans²; R. S. Goldman¹; ¹University of Michigan, Dept. of Matls. Sci. and Eng., Ann Arbor, MI 48109-2136 USA; ²Delphi Rsch. and Dev. Ctr., Warren, MI 48090-9055 USA

InSb is useful for a variety of device applications, including long wavelength infrared sources and magnetoresistive sensors. InSb films are often grown with a 14.6% lattice mismatch on GaAs substrates. Because of the high mismatch, InSb films initially grow in a Volmer-Weber mode, which consists of nucleation and coalescence of three-dimensional islands. The island growth introduces significant surface and interface roughness, which may impact the electron mobility. Furthermore, the large mismatch results in a high density of strain relaxation-induced defects including misfit and threading dislocations. The electronic properties of such highly mismatched InSb films tend to improve with increasing film thickness. However, the relative effects of dislocations and surface and interface roughness on the electron mobility of InSb/GaAs heterostructures are not fully understood. Therefore, we have investigated the evolution of the structural and electronic properties of highly mismatched InSb films, with thicknesses ranging from 0.1 to 1.5 μm. Atomic force microscopy, cross-sectional transmission electron microscopy, and high resolution X-ray diffraction show that the 0.1 μm films are nearly fully relaxed and consist of partially coalesced islands, which apparently contain threading dislocations at their boundaries. As the film thickness increases beyond 0.2 μm, the island coalescence is complete and the residual strain is decreased. Although the epilayers have relaxed equally in the $\langle 110 \rangle$ in-plane directions, the epilayer rotation about an in-plane axis (epilayer tilt) is not equal in both $\langle 110 \rangle$ in-plane directions. Furthermore, epilayer tilt which increases the substrate offset (reverse tilt) is evident in the [110] direction. High resolution transmission electron microscopy (HRTEM) indicates the presence of pure edge dislocations, which relieve ~12.8% of the 14.6% lattice-mismatch. The remainder of the misfit is

relaxed predominantly by β -type 60° dislocations. The threading dislocation density decreases as a function of film thickness, dropping from $\approx 10^{11}\text{cm}^{-2}$ for the $0.1\mu\text{m}$ films to $\approx 4 \times 10^8\text{cm}^{-2}$ for the $1.5\mu\text{m}$ films. The reduction in threading dislocation density as a function of film thickness is consistent with a significant increase in electron mobility. The other structural features, including the surface and interface roughness, do not appear to impact the electron mobility in these InSb films. Together, these results suggest that carrier scattering from threading dislocation is the primary mobility-limiting mechanism in highly mismatched InSb films.

2:40 PM, V5 +

Influence of Misfit Dislocations on Island Morphology in Large Lattice Mismatched Epitaxial Growth: *Vidyt Gopal*¹; Alexandre L. Vasiliev¹; En-hsing Chen²; Eric P. Kvam¹; Jerry M. Woodall¹; ¹Purdue University, Schl. of Mats. Eng., 1289 Mats. Sci. and Elect. Eng. Bldg., W. Lafayette, IN 47907-1289 USA; ²Yale University, Dept. of Elect. Eng., Becton Ctr., P.O. Box 208284, New Haven, CT 06520-8284 USA

We have performed high resolution transmission electron microscopy (HREM) investigations of InAs grown on (001) GaP substrates by molecular beam epitaxy (MBE), a system with a lattice mismatch of 11%. InAs is a narrow bandgap semiconductor with potential applications in high speed transistors, infra-red detectors and magnetic field sensing devices. However, the development of InAs based device technology has been hampered by the lack of a suitable lattice-matched substrate. We have pioneered the MBE growth of InAs/GaP heterostructures. GaP is closely lattice matched with Si, hence successful growth of InAs on GaP holds the potential of integrating InAs with the dominant Si technology. Misfit dislocation development during low (<1-2%) lattice mismatched epitaxial growth has been studied extensively. In such systems, the epilayer grows in a planar (2D) manner, and the mechanisms of dislocation introduction are well understood following the work of Matthews and co-workers. However, when the lattice mismatch is large, as in the present case, the growth mode becomes 3D. Initial growth is in the form of islands, and the mechanisms of strain relaxation are fundamentally different. Initial misfit dislocation introduction occurred directly at island edges. The islands that contained fewer dislocations had a larger aspect ratio (height:diameter), and as dislocations were added the aspect ratio decreased. Thus, islands grew faster laterally than vertically. A continuous layer resulted at a nominal thickness of 5 nm, and further dislocation introduction occurred by a glide based mechanism. This effect of misfit dislocation introduction on island morphology during the early stages of growth is a result of the competing mechanisms of elastic and plastic deformation. In the relatively un-dislocated islands, the mismatch strain is partially relieved by the elastic deformation of crystallographic planes, which is most effective far from the constrained island/substrate interface. Hence, these islands grow vertically rather than laterally. However, as misfit dislocations are added, strain is relieved by plastic deformation, and the islands tend to relax back to a lower contact angle-i.e., a lower aspect ratio. The phenomenon of misfit dislocation introduction promoting the lateral growth of islands over vertical growth has also been observed in other high mismatch systems such as Ge/Si.

3:00 PM Break

3:40 PM, V6

The Correlation of Defect Profiles with Transport Properties of InAs Epilayers on GaP: *Hironori Tsukamoto*¹; En-hsing Chen¹; Vidyt Gopal²; Jerry M. Woodall¹; ¹Yale University, Dept. of Elect. Eng., P.O. Box 208284, 15 Prospect St., New Haven, CT 06520-8284 USA; ²Purdue University, Sch. of Mat Sci and Eng., 1285 EE Bldg., West Lafayette, IN 47907-1285 USA

Owing to its high electron mobility and high electron saturation drift velocity, InAs is a good candidate for THz device applications. This has motivated our group to pioneer the MBE of high quality InAs on GaP, even though there is an 11% lattice mismatch. We have previously reported that these InAs films have unique electronic properties associated with interface misfit dislocation intersections, including interface Fermi-level pinning, interface electron generation and scattering, and no carrier freeze out at low temperature [1]. Here, we report the correlation of carrier profiles and transport properties with threading dislocation density profiles for InAs films. We have modeled the carrier and mobility profiles for these InAs films as a first-order approximation of the measured transport properties. We show that the electron concentration

profile in InAs films can be written as a simple equation that is proportional to the inverse of a distance x from the InAs/GaP interface. Due to dislocation annihilation during growth, the dislocation density profile also varies as the inverse of distance from the InAs/GaP interface $D(x)=D_0/(x_0+x)$, where D_0 is a dislocation density (cm^{-2}) in the interface region x_0 . This correlation suggests that the threading dislocations act as donor dopants. Undoped InAs films with various thicknesses were grown on GaP using MBE. The details of the growth procedure have been reported elsewhere [1]. The 90° edge misfit dislocation intersection density was found to be $6.3 \times 10^{12}\text{cm}^{-2}$ from cross sectional TEM analysis. Sheet carrier density and carrier mobility were measured using the van der Pauw method. Assuming each threading dislocation core site to be a shallow donor dopant, the carrier profile, $N(x)$, was modeled as a function of the distance from an InAs/GaP interface as: $N(x)=N_0+N_s/(x_0+x)$. (1) N_0 is the constant background carrier density (cm^{-3}) of the InAs film and N_s is a sheet carrier density (cm^{-2}) at an InAs/GaP interface. x_0 is an effective triangular well thickness formed at the InAs/GaP interface due to Fermi level pinning [1]. This model was applied to different InAs films, assuming N_s , N_0 and x_0 as variable parameters. The curves showed good agreements with the experimental data. The average values of N_0 is $2-3 \times 10^{16}\text{cm}^{-3}$. For $2.025\mu\text{m}$ InAs film, $N_s=1.0 \times 10^{13}\text{cm}^{-2}$ and $x_0=12\text{nm}$. For a $0.5\mu\text{m}$ InAs film, $N_s=1.2 \times 10^{13}\text{cm}^{-2}$ and $x_0=15\text{nm}$. It is interesting to note that the average N_s value is very close to the misfit dislocation crossing or "Dreidl" density of $6.3 \times 10^{12}\text{cm}^{-2}$ [1,2]. These N_s values support the Dreidl defect model of carrier generation suggested in ref. 1. The $N(x)$ profile supports our assumption that threading dislocation core sites are donor dopants. We also investigated the carrier mobility profile of InAs films based on the dislocation scattering model: the carrier mobility is proportional to the inverse of a dislocation density. The conducting layer thickness ($t-x$) of samples was calculated to obtain a position of carriers that dominated the apparent carrier mobility of Hall measurement, using Eq.2: $N_s(x)=U_x tN(x)dx$. (2) where $N_s(x)$ is the sheet carrier concentration at x , and we assumed that Hall current flowed between a top surface t and a certain depth x in the InAs film during the measurement. Then ($t-x$) was determined by solving equations Eq.2 with varying x until the calculation of $N_s(x)$ corresponded to a measured sheet carrier density. The carrier mobility profile $\mu(x)$ of InAs film was investigated using Eq.3, $\mu N_s(x)=U_x tN(x) \mu(x) dx$ (3) where $\mu N_s(x)$ is the product of the measured mobility, μ , and sheet carrier density $N_s(x)$; and $\mu(x)=\mu_0/x^n$, for $x>0$, where $\mu_0=386$ is a fitting parameter, and $n=0.5$. It is a surprising and happy result that at room temperature, $\mu(x=2\mu)=20,000\text{cm}^2/\text{volt-sec}$, and good news for device applications.

4:00 PM, V7 +

Influence of Misfit Dislocations on the Mobility in Pseudomorphic High Electron Mobility Transistors Based on In_xAl_{1-x}As/In_{0.75}Ga_{0.25}As/InP Structures: *Randy S.D. Hsing*¹; Maria Naidenkova¹; Mark S. Goorsky¹; Randy Sandhu²; Michael Wojtowicz²; Patrick Chin²; Thomas Block²; Dwight Streit²; ¹University of California at Los Angeles, Mats. Sci. and Eng., 6532 Boelter Hall, P.O. Box 951595, Los Angeles, CA 90095-1595 USA; ²TRW Electronic Technology Division, Space and Elect. Grp., Redondo Beach, CA 90278 USA

The reduction of the misfit dislocation density at the interfaces between the channel and the barrier layers improves the electronic properties in InP-based pHEMT structures. Misfit dislocations that form primarily at the bottom interface between the channel and the buffer layer cause interfacial roughness at the top interface between the channel and the donor supply layer. This roughness is found to be a major cause of the mobility reduction. We demonstrate this influence of misfit dislocations on the surface morphology and transport properties of In_xAl_{1-x}As/In_{0.75}Ga_{0.25}As/InP pHEMT structures with lattice matched (X_{In}=0.52) and tensile strained (X_{In}=0.48) buffers with channel thickness in the range of 15-40nm. Both 60° mixed dislocations and 90° edge dislocations form at the interface between the strained In_{0.75}Ga_{0.25}As channel and the lattice matched InAlAs buffer or barrier layers. However, misfit dislocations were not present for the same channel structure grown on the tensile strained buffer layer, demonstrating that strain compensation leads to beneficial properties in these pHEMT structures. The surface morphology was also much smoother ($4-6\text{ \AA}$ r.m.s.) than that for the lattice matched case ($10-20\text{ \AA}$), and the room temperature mobility measurements show much higher values for the structures grown on the tensile strained buffer layer. With increasing dislocation density in the lattice-matched barrier structures, the room temperature mobility drops

from 12,000 cm²/V·s (channel thickness=150 Å) to 4,500 cm²/V·s (channel thickness=400 Å). For a given sample that possesses misfit dislocations, the differences in carrier scattering along different crystallographic directions corresponds to asymmetric distribution of the different misfit dislocations as determined by magneto-transport Hall bar measurements. In addition, the electrons that occupied the lowest quantum level showed a decreasing mobility with increasing temperature, while the electrons that occupied the second lowest quantum level showed a slight increase in mobility with temperature. Scattering of the lowest energy electrons is a direct result of the fluctuating potential caused by the imperfect In_xAl_{1-x}As/In_{0.75}Ga_{0.25}As interface (channel/spacer) as modeling shows that these carriers are confined near the top In_{0.75}Ga_{0.25}As/InAlAs barrier interface. The electrons at the second quantum level are distributed to both interfaces and show signs of strong scattering by the dislocations, as confirmed by modeling. The use of strain compensating buffer layers can eliminate the formation of misfit dislocations and roughness at the channel interfaces and thus lead to improved device performance.

4:20 PM, V8 +

Strain Relaxation and Defect Reduction in InGaAs by Lateral Oxidation of AlGaAs Channel: *Kuo-Lih Chang*¹; John Henry Eppel¹; Gregory W. Pickrell¹; Hung-Cheng Lin¹; K. Y. Cheng¹; K. C. Hsieh¹; ¹University of Illinois, Elect. and Comp. Eng., 208 N. Wright, 319B Microelectronics Lab., Urbana, IL 61801 USA

Heterogeneous growth of ternary semiconductors facilitates band gap engineering and expands device applications both optically and electrically as compared with their binary constituents. However, lattice mismatch is always a concern when growing strained layers. Two different growth technologies that have been used to yield high strain relaxation and low threading dislocations are compliant epitaxy and metamorphic epitaxy. For compliant epitaxy, a very thin deformable layer is used as the substrate. In contrast, metamorphic growth utilizes a thicker graded buffer layer before growth of the low-defect epitaxial layer. Recently, high-quality low-defect InGaAs grown on GaAs with strain up to 3.5% has been demonstrated by the metamorphic technique. Other than these two techniques, strain relaxation in an epi-layer can also be accomplished by oxidizing an underlying AlGaAs layer. Recently, it has also been reported that oxidation of a buried AlAs layer has induced strain relief in an overlying strained InGaAs layer. As much as 50%-90% relief of residual strain has been reported. [1,2] In this work, the strain relaxation and defect reduction in In_{0.25}Ga_{0.75}As and In_{0.4}Ga_{0.6}As grown on GaAs with an AlGaAs channel have been studied by cross-sectional transmission electron microscope and high-resolution x-ray diffraction. The samples have been grown by solid-source molecular beam epitaxy (SSMBE) at relatively low growth temperatures and low growth rates thereby minimizing the threading dislocation densities. The threading dislocation density of the as-grown material is as low as 10⁷ cm⁻² in a 2000Å In_{0.25}Ga_{0.75}As film. The indium composition and residual strain have been determined precisely by (2,2,4) and (-2,-2,4) diffraction x-ray analysis, which yields both in-plane and out-of-plane strain. With the underlying AlAs layer being laterally oxidized, the amount of residual strain has been again determined by high-resolution x-ray measurement. It is found that oxidation helps relieve some residual strain. In addition, the oxidation process removes all misfit dislocations along the interface due to material loss and exerts a stress to move the threading dislocations thereby reducing its density by an order of magnitude. This is a promising technique to create a low-defect template for subsequent epitaxy. [1] J. H. Seo and K. S. Seo, Appl. Phys. Lett. 72, 1466 (1998) [2] P. Chavarkar, L. Zhao, S. Keller, A. Fisher, C. Zheng, J. S. Speck and U. K. Mishra, Appl. Phys. Lett. 75, 2253 (1999).

4:40 PM, V9 +

Effects of Hot Electrons on Transconductance Dispersion in AlGaAs/InGaAs Pseudomorphic High Electron Mobility Transistor: *Kyoung Jin Choi*¹; Jong-Lam Lee¹; ¹Pohang University of Science and Technology (POSTECH), Dept. of Matls. Sci. and Eng., San 31 Hyojadong Nam-ku, Pohang, Kyungbuk 790-784 Korea

Hot electrons are produced at the gate edge of drain side during device operation, which cause the reduction of the open-channel drain current and the shift of threshold voltage. This was explained as the production of point defects by hot electrons, acting as trap site for electrons. However, no works on the direct observation for traps produced by hot

electrons have not been conducted yet. In this study, we applied hot electron stress to AlGaAs/InGaAs pseudomorphic high electron mobility transistors (PHEMTs) and observed the new traps using deep level transient spectroscopy (DLTS) responsible for the observed degradation. The role of traps on the degradation of PHEMTs was examined by measuring transconductance dispersion. The 0.8-um-gate AlGaAs/InGaAs PHEMTs with single recessed structure were fabricated. The gate current as a function of VGS exhibited the typical bell shape, which is due to collection of holes generated by impact ionization. The device was submitted to hot electron stress in the condition of Vgs=0.5V and Vds=7V, corresponding to a very high impact ionization regime. After the stress, the bell-shaped gate current was greatly decreased, and the two-terminal gate-to-drain leakage current was increased. It is proposed that reduction of the bell-shaped gate current resulted from the decrease of the electric field strength under the gate edge of the drain side due to the electrons captured in the created surface states. To find the role of hot electrons on the generation of point defects, we conducted capacitance DLTS measurements. In DLTS spectra of the unstressed device, two electron traps corresponding to DX-center and EL2 were observed. After the stress, there has been no significant change in the spectra of the electron traps, however a hole trap, which is frequently observed in n-type devices, was newly observed. The hole-like signals originate from the surface states existing between gate and source/drain electrodes[1]. When the reverse bias is applied to the gate, a high electric field is concentrated at gate edges toward source/drain electrodes. Thus, electrons are emitted from the gate onto the ungated surface, and depletion layer width under the ungated surface is increased. The increase of the depletion layer width leads to decrease of capacitance, namely, the evolution of hole trap-like signal in DLTS spectra. To find the role of hot electrons on the degradation of PHEMTs, transconductance dispersion were performed in the frequency range of 1 to 100000Hz. Unstressed devices showed no significant transconductance dispersion in the whole frequency range. But, transconductance was decreased as a function of frequency in stressed devices. This indicates generation of surface states between gate and source/drain electrodes. From these results, the origin of hot-electron-induced degradation in PHEMTs is discussed. [1] K.J.Choi and J.-L.Lee, Appl.Phys.Lett., 74(8), 1108(1999).

Session W. SiC Growth and Device Processing

Thursday PM Room: Driscoll Center
June 22, 2000 North - Pub

Session Chairs: Karen Moore, Motorola, Inc., Tempe, AZ 85284 USA; Carl-Mikael Zetterling, KTH, Royal Instit. of Tech., Vista, Sweden

1:20 PM, W1

Structural and Electrical Properties of 4H-SiC Epitaxial Layers Grown by Hot-Wall-CVD: *Guenter Wagner*¹; *Bernd Thomas*¹; ¹Institute of Crystal Growth, Max-Born-Str.2, Berlin 12449 Germany

Thick SiC layers with growth rates up to 10 μm/h have been grown in a horizontal low pressure hot-wall CVD reactor on 35 mm SiC wafers using silane and propane as precursors. Layers up to 40 μm in thickness with a variation of about ± 3% have been obtained. The surfaces of the grown layers have mirror like morphologies with small substrate correlated defects. The surface roughness besides such defects is ± 1 nm. The influence of the main process parameters like total flow, system pressure, C/Si ratio and growth temperature on structural and electrical properties have been investigated. Structural properties of 4H-SiC epitaxial layers have been characterised by x-ray-diffraction, electron channelling pattern in REM and light microscopy. Rocking curve maps taken before and after epitaxial growth show that epitaxial growth in the hot wall reactor improves the structural properties and achieves narrow FWHMs of rocking curves for epitaxial layers. By precise control of the C/Si ratio unin-

tentionally doped layers with $ND-NA = 6 \times 10^{13} - 2 \times 10^{14} \text{ cm}^{-3}$ have been grown on Si faces. SIMS measurements showed that the background doping level of acceptors like B and Al is below $2 \times 10^{14} \text{ cm}^{-3}$. The donor concentration characterised by C-V measurements of intentionally doped layers was proportional to the nitrogen flow in a wide range. The doping variation across the wafer diameter is below 15 %. The presented results stimulate further experiments on in situ doping of 4H-SiC epitaxial layers with p-dopants and open the opportunity for the preparation of p-n junction devices.

1:40 PM, W2 +

Processing Effects of Controlled N-type and P-type Doped SiC Epitaxy for Use in Dual-Gate JFETs: *Michael C. David Smith*¹; Jeffrey B. Casady¹; Michael S. Mazzola¹; Stephen E. Sadowl¹; Pankaj B. Shah²; Mark C. Wood²; ¹Mississippi State University, Elect. and Comp. Eng. Depts., Emerging Matls. Rsch. Lab., P.O. Box 9571, Mississippi State, MS 39762-9571 USA; ²U.S.Army Research Laboratory, Sensors and Electro. Dev. Direct., Adelphi, MD 20783 USA

In the absence of practical diffusion of dopants in SiC, devices are fabricated exclusively with ion implantation and epitaxial growth. Many of these devices require that precisely controlled doped layers of alternating p and n-type layers be grown via epitaxy either prior to or during the device process. While many such devices have been reported (for example GTO's, JFET's, and BJT's), little has been documented on the exact methods used for growing these layers. Issues still needing to be addressed include the use of single or multiple reactor tubes for different type dopants, possible residual contamination or compensation resulting from growth of p and n-type in the same tube, and memory effects. To examine these issues, we chose to grow layers for a Dual-Gate JFET (DG-JFET) consisting of a buried p+ gate (4H-SiC Si-face substrate) layer, n-type channel layer doped in the low 10^{16} cm^{-3} , and top p+ gate layer. These particular devices are designed to be normally-off, with a pinch-off voltage just above zero volts. These desired parameters dictated the doping concentration and thickness of the n-type channel epitaxial layer. Following the one-dimensional design and two-dimensional simulation using Atlas software from Silvaco, the actual fabrication of these devices began with the growth of n channel and p+ cap epitaxial layers on 4H p-type SiC substrates. The growth was performed in a horizontal cold-wall CVD reactor on a graphite susceptor at a set point of 1535°C . The n channel layer and p+ cap layer were grown using fixed the Si/C ratio to establish an n-type doping level of $2 \times 10^{16} \text{ cm}^{-3}$ and the introduction of trimethylaluminum (TMA) to establish degenerate p-type doping. The two layers were first grown consecutively in separate n and p+ growth runs, and then later in one continuous growth run, transitioning from n to p+. These techniques both produced excellent results, in terms of controlled doping, thickness, and uniformity, and thus demonstrated that a single growth run can yield controlled n-type to p-type transitions. Of utmost concern throughout has been the contamination of the system with TMA and the resulting p-type doping effects, but subsequent growth runs indicate that controllable n-type growth can resume after purging the system. Related fabrication and characterization details of these DG-JFET's will be reported in the full presentation.

2:00 PM, W3 +

Influence of Surface on Stacking Sequence: *Ulrike Grossner*¹; Juergen Furthmueller¹; Friedhelm Bechstedt¹; ¹Friedrich-Schiller-Universitaet, IFTO, Max-Wien-Platz 1, Jena 07743 Germany

One of the most outstanding properties of group-III nitrides and silicon carbide is the formation of polytypes. Whereas the research on nitrides is mainly focused on 3C and 2H, silicon carbide shows a much larger variety of polytypes. Of the more than 200 the hexagonal 4H, 6H, 2H, and the cubic 3C are the most common. The most difficult business concerning such materials is to control growth conditions in a way to produce pure polytypes by standard processes. Besides some theoretical investigations also quite a lot of more or less empirical studies of pressure, temperature, and dopant control are published up to now. For the 4H-(0001), the 6H-(0001), as well as for the 3C-(111) surfaces of SiC a $\sqrt{3} \times \sqrt{3}$ reconstruction exists and is well understood. The reconstruction geometry is represented by an adatom model with one silicon atom in a T4 position. To clarify the influence of the surface conditions, we studied different stacking sequences in the surface near region of the $\sqrt{3} \times \sqrt{3}$ 4H-(0001) and 6H-(0001), as well as the 3×3 and $\sqrt{3} \times \sqrt{3}$ reconstruction of 3C-(111). In detail we have performed total energy

optimizations with ultrasoft pseudopotentials in the framework of density functional theory in the local density approximation using the Vienna-Ab-Initio-Simulation-Package (VASP). The surfaces were simulated via repeated slabs containing 12 Si-C bilayers, and a vacuum region of about 6 bilayers thickness. For the 3C case we considered the intrinsic (ISF) and extrinsic (ESF) stacking faults found energetically favourable in the bulk [4]. Here the infinite stacking is broken by introducing one (ISF) or two (ESF) double layer(s) (<+...> and <+...>, respectively) with opposite orientation compared to the cubic stacking. The stacking sequences investigated for both the 4H- and 6H-(0001) surfaces can be interpreted as one to six bilayers with cubic stacking on top of a complete 4H (6H) elementary cell and the respective polytype below. Introducing stacking faults below the $\sqrt{3} \times \sqrt{3}$ 3C-SiC(111) surface becomes energetically favourable only from the third double layer below the surface. This effect can be enhanced by adsorption of B on top of this surface. On the other hand, under more Si-rich conditions (3×3 reconstruction, respectively) the introduction of stacking faults in the surface near region becomes less unfavorable. Also, the surface stacking of 4H-SiC and 6H-SiC is rearranged. A formation of up to 4 layers with cubic stacking on top of a 4H or 6H surface becomes favourable.

2:20 PM, W4

SiC Grown on Insulating Layers for Robust MEMS Applications: *J. Chen*¹; J. Scofield²; Andrew J. Steckl¹; ¹University of Cincinnati, Nanoelectro. Lab., 899 Rhodes Hall, Cincinnati, OH 45221 USA; ²Air Force Research Laboratory, Wright-Patterson AFB, OH 45433 USA

SiC is a promising material for the fabrication of MEMS sensors and controllers operating in extreme environments due to its high Young's Modulus and toughness, chemical inertness, and radiation resistance. MEMS applications require large area uniform SiC thin film be formed on 3-D structured sacrificial layers such as SiO_2 , Si_3N_4 and poly-Si. Fortunately, CVD is excellent in growing conformal films on structured substrates. Recently, we have successfully grown well-ordered cubic SiC(111) on these amorphous and polycrystalline layers directly, which provides an alternative material system for making robust MEMS devices. In this paper, we report the growth of cubic SiC with organosilanes (silacyclobutane-SCB and trimethylsilane-3MS) on SiO_2 -covered Si(100). A comparison to SiC growth on Si_3N_4 and poly-Si is presented in terms of SiC film quality and subsequent MEMS device characteristics. The oxides (30 to 100 nm) were thermally grown on Si(100) substrates. In addition, Si(100) with native oxide and $3 \mu\text{m}$ thick P-doped SiO_2 film were used as substrates. For all SiC growth experiments, the flow rates are 1 slm for hydrogen, 40 sccm for 3MS or SCB. The growth temperature ranged from 1000 to 1300°C . The SiC growth rate at these conditions is up to $1 \mu\text{m}/\text{min}$. The surface and interface quality were examined by SEM. The top surface and the interfaces of SiC/ SiO_2 and $\text{SiO}_2/\text{Si}(100)$ are generally smooth. The voids normally generated during growth of SiC directly on Si are not observed in this case at either interface. In FTIR spectra, only the Si-C signal is observed after subtracting the SiO_2 -related background. This indicates that the grown film is primarily SiC. X-ray diffraction spectra show cubic SiC oriented in the (111) direction was always grown. The XRD linewidth is around 0.25° for SCB growth and 0.21° for 3MS growth, which is similar to those of SiC grown on Si with the traditional two-step (carbonization plus growth) method. We have fabricated several static micro-electro-mechanical (MEMS) structures on these SiC films using surface micromachining processes similar to those utilized for Si MEMS manufacture. Measured material properties and performance characteristics of these cantilever beam and diagnostic test structures are also presented. Our initial results indicate good potential for the development of a multi-layer SiC MEMS process which requires the growth of structural films on insulating sacrificial layers.

2:40 PM, W5 +

Radio-Tracer Identification of W- and Ta-related Deep Levels in Silicon Carbide: *J. K. Grillenberger*¹; N. Achtziger¹; G. Pasold¹; R. Sielemann²; W. Witthuhn¹; C. Huelsen¹; ¹University of Jena, Max-Wien-Platz 1, Jena 07743 Germany; ²Hahn-Meitner-Institut Berlin, Glienicke Str. 100, Berlin 14109 Germany

Tantalum is used in or as the growth containment for Silicon Carbide crystals. In both cases, tantalum is present in the growth chamber and its incorporation in the growing crystal or layer is to be expected. Due to its extreme thermal stability, tungsten may play a similar role in the future. In order to understand the electronic properties of these impurities in

SiC, we are investigating band gap states of Ta and W in three different polytypes (4H, 6H, 15R). To establish a definite correlation between a band gap state detected by Deep Level Transient Spectroscopy (DLTS) and a certain element, we are using the concept of radioactive transmutation. The characteristic concentration change of radioactive isotopes serves as a unique fingerprint which is detected by sequential DLTS measurements during the elemental transmutation. All measurements were done on n-type epilayers with a net donor concentration in the mid 10^{15} cm^{-3} range. Doping with radioactive isotopes was done by recoil implantation at the Cyclotron (ISL) of the Hahn-Meitner Institute in Berlin. The radioactive isotopes ^{177}Ta or ^{178}W were produced in a holmium target foil by a nuclear reaction induced by a 90 MeV ^{16}O beam or a 85 MeV ^{18}O beam, respectively. The reaction products are ejected from the Ho foil and are directly implanted into the samples. Both isotopes transmute to hafnium. In addition, doping with stable isotopes was done at the ion implanter JULIA in Jena with multiple energies between 1 and 6.2 MeV in order to create an approximately rectangular depth profile with a mean concentration of 2×10^{14} cm^{-3} . Performing these experiments we could definitely identify one Ta-related level in the upper part of the band gap in each polytype. The level energies exhibit a clearly resolved splitting due to inequivalent lattice sites. Roughly speaking, the radiotracer experiment is used for identification, whereas further properties are measured on samples implanted with stable Ta due to the higher concentration achievable. We also could definitely identify two levels which are due to defects involving or being identical to exactly one W atom. Our experiments exclude Hf-related deep states in the part of the band gap investigated. The data may be used to predict the consequences of a Ta or W incorporation on electrical properties of SiC. In addition, DLTS can now be used as a fast and convenient tool to quantify the incorporation of these elements in a specific crystal. Furthermore the polytype dependence of the energy level position follows the Langer-Heinrich rule and confirms our earlier prediction of the conduction band offset (0.22 eV between 4H and 6H).

3:00 PM Break

3:40 PM, W6

Light Emission from Electron-Hole Recombination in 4H and 6H MOSFETs: *P. J. Macfarlane*¹; R. E. Stahlbush¹; ¹Naval Research Laboratory, Code 6816, 4555 Overlook Ave., Washington, DC 20375-5320 USA

Power devices fabricated with SiC are an appealing alternative to Si because compared with Si, SiC has a larger breakdown field, a wider bandgap, and higher thermal conductivity. Unlike other wide bandgap semiconductors, SiC can be thermally oxidized to form SiO_2 . However, interface trap densities in SiC MOSFETs are significantly larger than in Si MOSFETs. Here, we use a novel measurement technique based on imaging light emission due to electron-hole recombination occurring in the channel region of 4H and 6H n-type MOSFETs. The emission from the transistors is produced by alternately driving the channel between accumulation and inversion using what is essentially the same circuit as that used for charge pumping measurements. Light emission from the resulting electron-hole recombination is collected with a microscope and focused on a backside illuminated CCD detector, cooled to -100°C to enhance sensitivity. The MOSFETs examined were fabricated at Purdue University. The 51.7 and 53.6 nm thick gate oxides were grown on 6H and 4H wafers, respectively, by wet thermal oxidation at 1150°C , followed by a wet anneal at 950°C to reduce the interface trap density. Effective channel mobilities of the 6H and 4H MOSFETs were determined by IV measurements to be 70 and 2.5 cm^2/Vs , respectively. The light emission from the SiC devices originates from both interface and bulk traps. In contrast, the emission from Si MOSFETs is only due to bulk recombination. Comparing the light intensities from Si, 4H and 6H devices, the emission is an order of magnitude larger from 4H transistors than from 6H MOSFETs and the emission from both SiC devices is approximately 1000 times larger than from Si MOSFETs. Several characteristics of the results strongly suggest the light from the SiC transistors results primarily from interface trap recombination. By altering the time the channel is cycled into inversion, the progress of electron flow into the channel can be imaged with this technique. For the shortest inversion times, only interface traps in the regions around the source and drain emit. Increasing the inversion time enlarges the emitting areas until light is observed from under the entire gate. Using the imaging technique in this manner, we

observe that the electron flow in the 4H devices is 2 to 3 orders of magnitude slower compare with the 6H transistors. The difference is due the 4H MOSFETs' lower mobility and higher interface state density. In sum, we will show that this light emission technique an effective method for investigating interface traps and their effects on SiC MOSFET performance. In addition, we will present emission images that exhibit extended defects beneath the channels of the SiC MOSFETs. We thank J.A. Cooper and M.K. Das for providing the SiC MOSFETs examined here.

4:00 PM, W7

MOS Interface Characteristics for n- and p-type 4H-SiC: *Michael A. Capano*¹; James Kretchmer²; ¹Purdue University, Elect. and Comp. Eng. Depts., 1285 Electrical Engineering Bldg., West Lafayette, IN 47907-1285 USA; ²General Electric, Corp. Rsch. and Dev., 1 Research Circle, Niskayuna, NY 12309 USA

Proper functioning of any metal-oxide-semiconductor field-effect transistor (MOSFET) depends critically on the semiconductor-oxide interface characteristics. Desired MOS characteristics include a low effective fixed charge density (Q_f) and a low density of interface states (D_{it}). The situation for SiC MOSFET technology is no exception. Typical values for the fixed charge density in 4H-SiC fall into the range of $1\text{-}5 \times 10^{12}$ cm^{-2} , and values for the density of interface states have been reported to be as low as the mid- 10^{10} cm^{-2} eV^{-1} near the middle of the 4H-SiC band gap. Unfortunately, the density of interface states increases exponentially near the conduction band edge, with D_{it} exceeding 10^{13} cm^{-2} eV^{-1} in some cases. High D_{it} values are suspected as being a principal reason why the channel mobility is so poor in 4H-SiC MOSFETs. Previous measurements have shown the channel mobility to increase as the annealing temperature for source/drain implants decreases. In those measurements, the gate oxide was thermally grown. More recent measurements have shown that channel mobilities can be as high as 70 cm^2/Vs if a deposited oxide is used in processing 4H-SiC MOSFETs. However, a quantitative relationship between channel mobility and MOS interface characteristics has not yet been established. This presentation attempts to deal with the question: what is the relationship between channel mobility and MOS interface properties? The approach is to measure the characteristics of 4H-SiC MOS capacitors using photo-CV and conductance methods. A first set of samples consisted of a high-temperature oxide (HTO) deposited onto p-type 4H-SiC epilayers (5×10^{15} cm^{-3} doping) to a thickness of 50 nm. The flat-band voltage shift with and without a 950°C reox anneal in wet O_2 is ≈ 8 V and ≈ 22 V, respectively, indicating poor interface quality ($\approx 1.542 \times 10^{12}$ cm^{-2} ; -2.5 V). A second set of samples were subjected to simulated implant activation anneals between 1200°C and 1400°C , corresponding to the range of temperatures examined in the channel mobility study. Following the simulated anneals, a thermal oxide was grown at 1150°C in wet O_2 on all samples. Both n-type and p-type samples were used. Photo-CV measurements on the n-type samples showed no significant differences with temperature, with a flat-band voltage of 1.5V observed for all samples ($\approx 1.542 \times 10^{12}$ cm^{-2} ; 0V). Results observed from the p-type samples are more complicated. Flat-band voltages varied from ≈ 12 V to as low as ≈ 3.6 V, depending on the anneal temperature. Conductance measurements on these samples are in progress. These results will be discussed from the perspective of better understanding channel mobility in 4H-SiC MOSFETs. The authors acknowledge support from DARPA under contract number MDA972-98-C-0001.

4:20 PM, W8

Amorphous Aluminum-Oxynitride Gate Dielectric Layers for SiC MISFET Devices: *Henry Luten*¹; Timothy Metzger¹; Guang-ji Cui¹; Wen-yi Lin¹; Jerome Schmitt¹; Andrew Hunt¹; X. W. Wang²; T. P. Ma²; ¹MicroCoating Technologies, Inc., 3901 Green Industrial Way, Chamblee, GA 30341 USA; ²Yale University, Elect. Eng. Dept., Ctr. for Microelect. Mats. and Struct., 15 Prospect St., New Haven, CT 06520-8284 USA

Conventional silicon dioxide films thermally-grown on silicon carbide (SiC) have not proven to be successful for service as high-quality gate dielectric layers for complementary metal-insulator-semiconductor (MIS) transistor device structures. There is a critical need, therefore, for superior thin film gate dielectric technology to enable development and propel forward the application of SiC power transistors. Among other alternative candidates, AlN films hold great potential to serve as the gate dielectric because of its higher dielectric constant (8.5) as compared to SiO_2 (3.9), and also because of its wider bandgap than other high permit-

tivity materials such as silicon nitride, etc. However, attempts so far in making AlN films with sufficient quality to serve as a viable gate dielectric have failed due to high leakage currents as well as high densities of dielectric charge and interface traps. In this work, we report promising results from our initial experimental depositions of device-quality amorphous AlON, using an anaerobic adaptation of our atmospheric pressure Combustion Chemical Vapor Deposition (CCVD) process. In this variation an inert purge gas flow bathes the hot SiC wafer surface and growing AlON film in order to shield them from air oxidation. This allows for deposition of high quality aluminum nitride-based materials. Scanning electron micrographs display dense, continuous, defect-free thin films. Test capacitors composed of 225 nm thick AlON layers on SiC substrates (Cree Research, Inc.) were completed by evaporation of aluminum electrodes. Post-deposition annealing steps both before and after metallization served to improve electrical properties of test MIS structures. Electrical testing of the initial MIS capacitors revealed low leakage current densities in both accumulation and inversion modes ($< 4 \times 10^{-4} \text{ A/cm}^2$ @ an operating field of -3 MV/cm , for the former and $< 2 \times 10^{-7} \text{ A/cm}^2$ @ $+4.8 \text{ MV/cm}$, or $+100 \text{ V}$, for the latter). Furthermore, they displayed high breakdown electric field with no breakdown at -4 MV/cm or -100 V , the maximum voltage available at the time of the experiment. In addition, we estimate low dielectric charge density ($N_{ot} \sim 6-7 \times 10^{11} / \text{cm}^2$) and interface-trap density ($N_{it} \sim 2 \times 10^{11} / \text{cm}^2$), while the relative dielectric constant remained high (~ 8.5). In sum, these results characterize a promising power transistor gate dielectric material. We will briefly describe the proprietary process and provide the results of materials characterization, device processing and electrical testing as well as future plans for the development of this technology for applications in power transistors.

4:40 PM, W9 +

Etching of Silicon Carbide for Device Fabrication and Via-Hole Formation: *F. A. Khan*¹; L. Zhou¹; A. Daga¹; D. Dumka¹; I. Adesida¹; ¹University of Illinois at Urbana-Champaign, Depts. of Elect. Eng. and Microelectro. Lab., 208 North Wright St., Urbana, IL 61801 USA

Silicon Carbide (SiC) is a wide bandgap semiconductor with potential applications for radiation resistant, high power, high frequency, and high temperature devices in the automotive, aerospace, power-generation and petroleum industries. Static induction transistors, metal-semiconductor-field effect transistors (MESFETs), and metal-oxide-semiconductor field effect transistors (MOSFETs) are examples of devices that have been realized in this material. Another important application of SiC is as a substrate for GaN heterostructures. Due to the superior thermal properties of SiC and the close lattice-matching of SiC and GaN, semi-insulating SiC has now become the material of choice as a substrate. Heterostructure field effect transistors (HFETs) fabricated in GaN on SiC have recorded the highest power density of any III-V HFETs. To properly conduct the heat away from the GaN HFET channel, it is pertinent to adopt one of the techniques that has been used for the realization of high power circuits in other III-V materials. This is the via-hole process where it is necessary to etch materials with thicknesses as high as 50 to 200 μm . Etching of SiC is non-trivial with wet etching only possible using electrochemical techniques. Conventional reactive ion etching produces very low etch rates which are not suitable for deep etching as might be needed in via-hole applications. High plasma techniques such as inductively-coupled plasma reactive ion etching (ICP-RIE) are versatile for achieving high etch rates with minimal damage to etched surfaces. We have investigated the etching of SiC using ICP-RIE using various SF₆-based mixtures with Ar, O₂ and Cl₂. Etch rates and profiles have been investigated as functions of gas flow rate, bias voltage, pressure, and ICP power. We have achieved etch rates in excess of 1 mm which are suitable for via-hole applications. Investigations as a function of bias voltage have revealed a non-linearity in the etch rate variation with bias voltage. A detailed study of this regime using chemically assisted ion beam etching technique will be presented to understand the role of physical mechanisms in the etching. Smooth surfaces and low damage are important for device fabrication; we will present AFM studies of etched surfaces and Schottky diode measurements on etched SiC epi-layers. Results of Auger electron spectroscopy on these surfaces will also be presented. We have developed viable mask processes using evaporated and electroplated Ni for the etching of very deep structures in SiC. Applications of these masks and ICP-RIE to the formation of via-holes (with $> 200 \text{ nm}$ depth) for GaN/AlGaN HFETs on SiC will be demonstrated.

5:00 PM, W10 +

A Novel CMOS-Compatible Deep Etching Process for Silicon Carbide using Silicon Shadow Masks: *Andrew Ryan Atwell*¹; Jon S. Duster¹; Kevin T. Kornegay¹; Robert Okojie²; ¹Cornell University, Sch. of Elect. Eng., 323 Phillips Hall, Ithaca, NY 14853 USA; ²NASA, Glenn Resch. Ctr., Instrument. Controls Div., 21000 Brookpark Rd., M/S 77-1, Cleveland, OH 44135 USA

A novel process for Deep Reactive Ion Etching (DRIE) in 6H-Silicon Carbide (SiC) using a sacrificial Silicon (Si) wafer as the etching shadow mask has been developed. We have leveraged off of the existing DRIE technology for Si to create a shadow mask for DRIE of SiC. Current technology exists for an anisotropic, through-wafer etch of Si using a PlasmaTherm SLR-770 etcher, but it does not currently exist for SiC. Isotropic wet chemical etches exist for SiC, but the use of a reactive ion etch will yield an anisotropic sidewall and flat and uniform etched structures. To etch SiC at a practical rate requires RF powers so high that conventional metal masks are quickly sputtered away. Furthermore, depositing and patterning thick metal masks is itself a technological challenge as the best mask suitable for SiC etching, nickel, has very high stress and is difficult to adhere to substrates when a layer thicker than 1000 angstroms is deposited using physical vapor deposition. In addition, eliminating the use of electroplating for thick metal masks or the use of exotic masking materials like Indium Tin Oxide requiring a specialized or dirty deposition chamber means that our process is more suitable for general microfabrication facilities. To demonstrate our process, we have used a patterned and etched sacrificial Si wafer as a shadow mask for SiC. Even though the etching selectivity between SiC and Si is not high, the thickness of a Si wafer ($\sim 400 \mu\text{m}$) gives enough masking material that the deep etch into SiC can be performed. First, we transferred our layout patterns to the sacrificial Si wafer using traditional photolithography. Next, the PlasmaTherm SLR-770 was used to etch completely through the Si wafer forming the shadow mask. Photoresist was then spun onto the SiC wafer and the Si shadow mask was attached to the SiC wafer. After curing (solvent bake), the photoresist was flood exposed and developed to remove it from surface of the SiC in the clear field of the Si shadow mask. Then the wafers were etched in our Magnetron Ion Etcher (MIE) at a rate of 700 nm/min using an SF₆ plasma. Finally, the Si shadow mask was released with resist stripper. In summary, we have formed 60 μm thick SiC membranes in 200 μm thick SiC wafers. The sidewall profiles show a high degree of anisotropy and the membranes are uniformly flat.

Session X. Silicon Integration Issues: Metallization and Low-K Dielectrics

Thursday PM Room: Centennial Halls
June 22, 2000 Cafeteria

Session Chairs: Masanori Murakami, Kyoto University, Dept. of Matls. Sci. and Eng., Sakyo-ku, Kyoto 606-8501 Japan; King-Ning Tu, University of California-Los Angeles, Dept. of Matls. Sci. Eng., Los Angeles, CA 90095-1595 USA

1:20 PM, X1+

Improved Shallow Junction Integrity using Single Crystalline CoSi₂: *Y. H. Wu*¹; K. T. Chan¹; S. B. Chen¹; W. J. Chen¹; Albert Chin¹; ¹National Chiao Tung University, Dept. of Electr. Eng., 1001 Ta Hsueh Rd., Hsinchu 30050 Taiwan

To continuously scaling down the VLSI technology, shallow junction with good electrical characteristics is required. To reduce the Si consumption of shallow junction, the thickness of formed silicide also needs to be scaled. Because of the scaled junction thickness, metal spiking from silicide may have high probability to penetrate shallow junction and create large leakage current. Furthermore, the thinner silicide thickness may have higher sheet resistance and poorer thermal stability due to

thickness non-uniformity of poly-crystalline structure. Although these difficulties can be solved using raised source-drain CoSi₂ junction and demonstrated excellent junction performance in 0.05 μ m technology, this technology may be targeted to be used for sub-0.13 μ m generation. In this study, we have developed a simple process to improve the performance CoSi₂ shallow junction. P+-n junction is first formed by BF₂+ implantation and RTA. To form single crystal CoSi₂, the native oxide between deposited Co and Si is suppressed by using HF-vapor passivation and in-situ desorption. Then 50nm CoSi₂ is formed by Co deposition and two-step RTA. In comparison with sputtering clean or ultra-thin 1nm Ti pre-layer, this method is very simple and reproducible without sputtering damage or B condensation in Ti-O layer. From cross-sectional TEM, single crystalline CoSi₂ is formed with much improved thickness uniformity than conventional polycrystalline structure. The smooth thickness is further examined by scanning tunneling microscopy and RMS roughness is reduced from 0.7nm to 0.4 nm for poly and single crystal structure, respectively. Smaller sheet resistance of 5 ohm/sq is measured for epitaxial CoSi₂ than 8 ohm/sq of poly crystal one. Low junction leakage current of <1x10⁻⁸ A/cm² is also measured for epitaxial CoSi₂ than 6x10⁻⁸ A/cm² for poly crystal structure. Good thermal stability of epitaxial CoSi₂ films is evidenced from the almost unchanged sheet resistance and junction leakage current after RTA up to 950°C. In contrast, the sheet resistance and leakage current are higher in control samples over 600-950°C temperature range, and becomes larger with increasing annealing temperatures above 850°C. The decreased leakage current and improved thermal stability is due to the decreased Co spiking in epitaxial structure; non-uniform Co diffusion through native oxide and grain boundary into Si is expected in poly crystal structure to create spiking. The improved stability of sheet resistance is due to the uniform thickness without agglomeration onto discrete islands as observed by TEM.

1:40 PM, X2

Abnormal Grain Growth of Cu Film Interconnects for Si-ULSI Devices: Miki Moriyama¹; Kentaro Matsunaga¹; Masanori Murakami¹; ¹Kyoto University, Depts. of Matls. Sci. and Eng., Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501 Japan

Recently, extensive efforts have been made to replace aluminum by copper films for the interconnect materials of the Si-ULSI (Ultra-Large Scale Integrated) devices. Although copper has higher mechanical strength, we have serious concern with reliability of the Cu interconnects, because interconnects which is strongly influenced by the film microstructure. In Cu thin films, specially, in the electroplated Cu films, abnormal grain growth with bi-modal grain size distribution was observed during room temperature storage. Such wide grain size distribution in the Cu films causes wide stress distribution in the interconnects, resulting in local deformation of the ultra-narrow interconnects. Therefore, to realize the highly reliable Cu interconnects, it is very important to prepare the Cu films with uniform grain sizes, and understanding of Cu grain growth mechanisms is mandatory. The purpose of the present study is to search a primary factor which induces abnormal grain growth of the Cu thin films during isothermal annealing at temperatures ranging from 298K to 773K. In order to understand the effect of stress intrinsic in the Cu films on the grain growth, microstructures of films with or without the rigid substrate were observed by transmission electron microscopy (TEM). The 100nm-thick Cu films were deposited onto the Si₃N₄ and rocksalt substrates by the radio-frequency sputtering technique. Free-standing Cu films were prepared by removing the films from the rocksalt substrates. These samples (with or without the substrates) were annealed isothermally at temperatures ranging from room temperature to 773K in 5% H₂/N₂ mixed gas or in vacuum. The grain growth rates of the Cu films annealed with or without the substrates were compared. In free-standing Cu films, no grain growth was observed during room temperature storage. However, significant grain growth was observed in the Cu films which were annealed with the Si₃N₄ and rocksalt substrates, and the wide grain size distribution of the Cu films, and two different grain growth rates were observed during room temperature annealing. The largest grain size was about 1 μ m which was about 10 times larger than the film thickness, while majority of the grains were smaller than 50nm (half of the film thickness). The present result suggests that the grain growth kinetics in Cu thin films was strongly influenced by the existence of the rigid substrates, indicating stresses in the films enhanced the grain growth. The detailed mechanism of the abnormal grain growth will be discussed at the conference.

2:00 PM, X3

Preparation of Low-k Porous SiO₂ Films by Chemical Vapor Deposition: Akira Fujimoto¹; ¹Tokyo Institute of Technology, Phys. Electro. Dept., 2-12-1 O-okayama Meguro-ku, Tokyo 152-8550 Japan

We succeeded in depositing porous silica films with TICS/H₂O/xylene CVD system. The highest resistivity and the lowest dielectric constant of the film after annealing processes were 10¹⁶ Ohm cm and 3.0, respectively. Low-dielectric insulator is required for the reduction of the RC delay time in ULSI. Porous silica film is an attractive candidate of the interlayer dielectric films. Usually, the film was fabricated by spin on glass (SOG) technique. In this work, we tried to deposit the porous silica films by CVD method. We had already developed a new SiO₂ CVD method using tetra-isocyanate silane (TICS, Si(NCO)₄) and water. We modified the system by addition of xylene into reaction gases. We expected that xylene molecules in the deposited films will act as spacers, and that the density of SiO₂ skeleton of the films will decrease. By removing the xylene molecules after deposition, porous SiO₂ film can be obtained. Firstly, we examined the dependence of film porosity on xylene addition. The film porosity was evaluated from the absorption coefficient corresponding to Si-O bonds around 1070 cm⁻¹ measured by FT-IR spectrometer. Under the condition that TICS partial pressure, water partial pressures and substrate temperature were 5 Torr, 30 Torr, and 80 Torr, respectively, films were deposited by varying xylene partial pressure from 0 to 100 Torr. Absorption coefficient of the films without xylene addition was 0.95 μ m⁻¹. It decreased to 0.78 μ m⁻¹ when xylene partial pressure was more than 60 Torr. Further decrement of absorption coefficient was observed by decreasing water partial pressure. The minimum absorption coefficient was 0.65 μ m⁻¹ which was obtained under the condition that TICS, water and xylene partial pressures were 5 Torr, 15 Torr and 80 Torr, respectively. For xylene removal process, samples were annealed in oxygen plasma. We used conventional parallel-plate 13.56MHz RF plasma system. Oxygen pressure and RF power density were 0.2 Torr and 1 W/cm², respectively. After the annealing for one hour at 300°, refractive index of the films became 1.40 which was lower than that of thermal oxide. However, dielectric constant was 6.5. The reason of the high dielectric constant was silanol bonds in the film which were confirmed by FT-IR spectrometry. To remove the silanol bonds, samples were annealed in nitrogen ambient. After annealing for one hour at 600°, dielectric constant decreased to 3.0. Resistivity was also improved from 10¹⁴ Ohm cm to 10¹⁶ Ohm cm.

2:20 PM, X4 +

High Frequency Characterization of Mega-Ohm Resistivity Si Formed by High-Energy Ion Implantation: Y. H. Wu¹; M. Y. Yang¹; S. B. Chen¹; C. P. Liao¹; Albert Chin¹; C. M. Kwei¹; ¹Industry Technological Research Institute, Electro. Rsch. Serv. Org., Hsinchu, Taiwan 30050; ¹National Chiao Tung University, Dept. of Electro. Eng., 1001 Ta Hsueh Rd., Hsinchu, Taiwan 30050

High resistivity Si is urgently required for Si based MMIC or high speed opto-electronic devices. Unfortunately, the current high resistivity Si has resistivity of only 1K to 10K ohm-cm that is still far away from semi-insulating III-Vs. However, the lower Si resistivity increases both transmission line loss and cross-talk noise of RF circuits. To reduce the high frequency substrate loss, ~100 μ m deep trench is required but this process is very difficult to be applied into current VLSI. Previously, we have reported that the Si resistivity can be largely increased by using simple Si ion implantation into Si substrate and ultra-fast carrier lifetime of 0.9ps is measured. However, the maximum implanted depth is only ~1 μ m that is insufficient for RF or high speed opto-electronic circuits application. Therefore, poor RF characteristic is measured because of the large loss from none implanted Si substrates. In stead of the heavier Si ion, in this study, we have used high-energy lighter proton ion to penetrate the entire 4-in substrate. The measured resistivity increases largely from standard ~10 ohm-cm to > 1 mega-ohm after implantation. The resistivity also increases as increasing implanted dosage. Because high resistivity can cover entire Si substrate depth, direct RF characterization can be performed. We have fabricated transmission line on this high resistivity Si and transmission loss or cross talk is measured up to 20GHz using a network analyzer with on wafer probe and de-embedding. Very low transmission line loss of 6.3 dB/cm is measured at 20 GHz that is 5 dB/cm lower than the same transmission line fabricated on standard Si with 1.5 μ m thick insulating thermal oxide. Low cross coupling of -80 dB/cm is measured that is important for low noise and mixed signal circuits. From

photo response of femto-second laser pulse, 1.1 ps carrier lifetime is also obtained, which is close to our previously measured value using Si-ion implantation. Therefore, the mechanism of achieving high resistivity Si is due to implanted defects. We have also studied the thermal stability on high resistivity dependent RF characteristics by annealing the implanted Si. Almost the same resistivity and RF loss are measured after 400°C annealing for 1hr. However, much degraded resistivity is measured after 600°C annealing. We have used cross-sectional TEM to further study the thermal stability, and the 600°C annealing related degradation is due to solid phase epitaxy of amorphous Si. However, the 400°C annealing stable high resistivity and low RF loss can already be used for VLSI back-end process integration.

2:40 PM, X5 Late News

Session Y. Organic Materials and Devices - II

Thursday PM Room: Centennial Halls
June 22, 2000 Main Lounge

Session Chairs: Vladimir Bulovic, Universal Display Corporation, Ewing, NJ 08618 USA; Zoran Popovic, Xerox Research Centre of Canada, Mississauga, Ontario 00229 Canada

1:20 PM, Y1 *Invited

Electronic Structure of Organic/Metal Interfaces Studied by Electron Spectroscopies and Kelvin Probe: Kazuhiko Seki¹; Eisuke Ito¹; Hiroshi Oji¹; Yukio Ouchi¹; Hisao Ishii¹; ¹Nagoya University, Rsch. Ctr. for Matls. Sci. and Dept. of Chem., Furocho, Chikusa-ku, Nagoya 464-8602 Japan

In many electronic devices using electronically functional organic materials, e.g. organic electroluminescent devices and organic solar cells, the interface of the organic material with metals or other organic layers plays an important role. There are many important factors determining the electronic structures at the interfaces, such as energy level alignment right at the surface, possible band bending to align the Fermi levels of the interface-forming layers, and possible chemical reaction or interdiffusion. We have been systematically studying such factors using various electron spectroscopies such as UV photoelectron spectroscopy (UPS), X-ray photoelectron spectroscopy (XPS), metastable atom electron spectroscopy (MAES), and Kelvin probe technique [1]. In this talk we will present our recent studies on (1) the possible existence of band bending to achieve the Fermi level alignment, and (2) the dependence of the structure and electronic structures at interfaces formed by the combination of p-sexiphenyl (6P) and Au or Mg in both organic-on-metal and metal-on-organic sequences. In the former, the deposition of thick TPD layer deposited on various metals under ultrahigh vacuum (UHV) was pursued by Kelvin probe technique. At the initial stage of deposition, there was a sharp decrease of the work function within a few monolayers corresponding the formation of an electric double layer [1], while there was little further change corresponding to the band bending up to a thickness of 100nm. Also the final values depends on metals, clearly showing that Fermi level alignment is not achieved, and electric equilibrium between the TPD and metal layers are not established. In the systems formed between 6P and Au or Mg, the growth mode of 6P strongly depended on the metal surfaces. On Au, 6P easily covers the metal surface, while significant amount of 6P was necessary for covering the Mg surface. Upon metal deposition on 6P, the metal atoms diffuse into 6P layer, and it is even difficult to form a metal layer at the top of the 6P layer.

2:00 PM, Y2

Effect of Side Groups on Electroluminescence of PPV Derivatives: Guangming Wang¹; Yuanzhen Xiang²; Xhunwei Yuan²; Zuhong Lu²; Yinkui Li³; ¹Nanyang Technological University, Adv. Matls. Rsch.

Ctr., Sch. of Appl. Sci., Nanyang Ave. 639798 Singapore; ²Southeast University, Lab. of Molecular and Biomolecular Elect., Nanjing 210096 PRC; ³National University of Defense Technology, Dept. of Matls. Eng. and Appl. Sci. Chem., Changsha 410073 PRC

A new field of research has been opened up, simulated by the interest form industry to use these conjugated polymers as active components in various display applications since the first reports on electroluminescence (EL) from conjugated semiconducting polymer poly(p-phenylene vinylene) (PPV), prepared by way of a solution-processable precursor. Then, many EL devices were researched by using the PPV and its derivatives. In addition, for the PPV derivatives with side groups, their films can be directly spin-cast form the solutions. On the other hand, related copolymers, comprising a combination of different arylene units, can be chemically tuned to provide a range of materials with considerably improved properties for this and other applications. By incorporating two different groups into a copolymer, local variations in the Π - Π^* electronic energy gap at both the molecular and supramolecular level can act to trap excitons, hindering their migration to quenching sites. Based on these considerations, we set out, therefore, to synthesize PPV derivatives and their copolymers that have regions of different Π - Π^* energy. The synthesized PPV derivatives are: poly(2-methoxy-5-butoxy phenylene vinylene) (MB-PPV), poly(2-methoxy-5-decoxy phenylene vinylene) (MD-PPV), poly(2-methoxy-5-hepoxy phenylene vinylene-co-2-methoxy-5-butoxy phenylene vinylene) (MHcoMB-PPV), poly(2-methoxy-5-nonoxy phenylene vinylene-co-2,5-dimethyl phenylene vinylene) (MNcoDM-PPV), and poly(2-methoxy-5-octoxy phenylene vinylene-co-2-methoxy-5-ethoxy phenylene vinylene) (MOcoME-PPV). It was found that the peak positions of absorption, excitation, and photoluminescence spectra for these PPV derivatives in the chloroform as solvent take red shift with the carbon number increase in the alkyloxy group, but their EL spectra change little. Although these EL spectra are quite similar, their EL density and efficiency are different. It was found that the EL intensity and efficiency of the PPV-derivative device increase with the carbon number increase in the alkyloxy group. In addition, the EL intensity of the copolymer PPV derivatives is stronger than that of the single PPV derivative, i.e., $I_{MNcoDM-PPV} > I_{MOcoME-PPV} > I_{MHcoMB-PPV} > I_{MD-PPV} > I_{MB-PPV}$. This may be due to that the local variations in the Π - Π^* electronic energy gap at both the molecular and supramolecular level can act to trap excitons, hindering their migration to quenching sites by changing the alkyloxy group in the PPV derivatives. We also studied EL properties of these PPV-derivatives blended with low weight molecule 8-hydroxyquinoline aluminum (Alq₃), and found that the different PPV derivatives possess various reactions between Alq₃ and these polymers.

2:20 PM, Y3

Electroluminescent Properties of Eu-Complex Doped Organic-Inorganic Polymers: A. V. Kukhta¹; E. E. Kolesnik¹; T. A. Pavich¹; M. I. Taubli¹; ¹Institute of Molecular and Atomic Physics, Skaryna Ave. 70, Minsk 220072 Belarus

The main problems of organic electroluminescent structures are their efficiency, and photo and temperature stability. Good results are widely obtained with polymers. We developed a new electroluminescent material on the basis of organic-inorganic polymer containing Eu complexes. It is known that inorganic glasslike polymer consisting of -Si-O- chains is highly chemically, thermally and radiation stable. They are very homogeneous and transparent. Introducing of different organic substituents into this chain gives the possibility to keep the main properties of inorganic polymer, and to improve flexibility, and to bond chemically activator molecules with matrix. We used -CH-CH₂- substituent. Homogeneous and very thin glasslike films can be easily obtained. Four ligand Eu complex on the basis of biketonate and phenyl rings is proposed as activator radiating in a red spectral region. This complex is the most stable and effectively luminescing. Its wide branched p-electron system gives intensive energy absorption. The absence of hydrogen atoms reduces luminescence quenching. In such a system a high luminophor concentration without noticeable luminescence quenching, and energy transfer from matrix molecules to activator can be reached. These films are intensively luminescing under electron beam irradiation without transparency changing. Note that this method is the best to find new effective and stable organic electroluminescent materials. Rare earth ions radiating in a blue and green spectral region can be also used with this ligand for creating a white colour electroluminescing luminophor. We created a simple electroluminescent cell consisting of ITO layer as a positive electrode, 60

nm Eu-activated above mentioned polymer, and aluminium layer as negative electrode. Active area was 4.4 mm². An intensive red electroluminescence was observed after voltage applying. The electroluminescence spectrum fully coincides with photoluminescence one. The electroluminescence intensity was not changed practically during 3 days. Luminescent properties kept constant after 2 months storage. Proposed material is very perspective for creating organic light-emitting diodes and displays.

2:40 PM, Y4

Preparation and Characterization of Polymer Gradient Glass: ShenKang Ruan¹; XianBi Yang¹; Ying Qi¹; LinYan Li¹; AiMing Zhong¹; MianZeng Su¹; ¹Peking University, Dept. of Matls. Chem., State Key Lab. of Rare Earth Matls. Chem. and Appl., Beijing 100871 PRC

The glass which has continuous variation of refractive index either in the radial or the axial direction is called gradient glass. This material has been extensively applied in optical and optoelectronic device such as compact photocopies, communication relay systems, medical imaging systems, etc. A new type of polymer gradient glass has been successfully prepared by the sol-gel method in our laboratory. We first incorporated poly-dimethylsiloxane (PDMS) with tetraethyl(ortho)siloxane (TEOS) by sol-gel method, and obtained an organic and inorganic hybrid system. Then, we added Ti(OBu)₄ to this system by sol-gel method. Finally, we obtained a new type of polymer gradient glass. This material shows good optical transparency and gradient property. Moreover, it is superior to the traditional gradient material in hardness and toughness.

3:00 PM Break

3:40 PM, Y5 *Invited

The Interface Energetics and Growth Modes Between Organics and Indium Tin Oxide: E. W. Forsythe¹; Q. T. Le²; L. Yan²; Yongli Gao²; M. A. Abkowitz³; L. J. Rothberg³; F. Nuesch³; ¹Army Research Laboratory, 2800 Powder Mill Rd., Adelphi, MD 20904 USA; ²University of Rochester, Dept. of Phys. and Astro., Rochester, NY 14627 USA; ³University of Rochester, Dept. of Chem., Rochester, NY 14627 USA

We will report on the growth modes and interface energy characteristics of N,N'-bis-(1-naphthyl)-N,N'-diphenyl-1,1-biphenyl-4,4'-diamine (NPB) and copper phthalocyanine (CuPc) on indium tin oxide (ITO). The interface properties are correlated with the hole injection efficiency. The growth modes of NPB and CuPc on ITO have been measured using atomic force microscopy. The room temperature NPB growth mode is initially islands, which coalesce at an effective film thickness of 15 nm. Alternatively, the CuPc organic film grows layer by layer. Subsequent NPB films deposited onto the CuPc film also grow layer by layer. Because NPB is trap free, a direct and self-consistent measure of the injection efficiency as a function of ITO surface morphology and CuPc contact layer can be determined at a given applied field from the ratio of the measured dark current to the calculated trap free space charge limited current. The trap free space charge limited current is calculated from the time of flight drift mobility measured in the same specimen at the same applied field. In this way it is determined that hole injection is contact limited from as-received ITO. Further when a 15.0 nm thick CuPc layer is deposited onto the ITO the injection efficiency decreases compared to devices with no CuPc interlayer. In addition, we shall report the interface energetics between NPB and acid or base treated ITO using photoemission spectroscopy. Here, the ITO effective work function is increased or decreased by the absorbing monolayers of acids or bases on the ITO surface, respectively. The interface between ITO and organic films is important to the performance of organic based light emitting diodes. This work was supported in part by DARPA DAAL01-96-K-0086 and NSF DMR-9612370.

4:20 PM, Y6

Electroluminescence of Polymer with 8-Hydroxyquinoline: Jian-Ming Ouyang¹; Le-Xiao Zhang¹; ¹Jinan University, Dept. of Chem., Guangzhou 510632 PRC

Although many polymers have been used as emitting in EL devices, the quest for polymer analogs of 8-hydroxyquinoline-based metal chelates for EL applications has been a challenging task. These metal chelate polymers are non-traditional polymers and are usually associated with considerable handling difficulties. The insoluble and intractable nature of these polymers makes them amenable to the self-assemble growth. Some polymeric metal chelate derivatives of 8-hydroxyquinoline have been reported and light emitting diode made from these chelates have been

reported. We have synthesized a series of amphiphilic complexes with 8-hydroxyquinoline and fabricated several EL devices with the Langmuir-Blodgett films of these amphiphilic complexes as emitting layer. In this paper, a novel polymer with 8-hydroxyquinoline has been synthesized and EL device with this polymer as emitter will be studied.

4:40 PM, Y7 Late News

Session Z. Ordering in Semiconductor Alloys

Friday AM Room: Driscoll Center North
June 23, 2000 Ballroom A/B

Session Chairs: Alex Zunger, National Renewable Energy Laboratory, Golden, CO 80401 USA; Eric Jones, Sandia National Laboratories, Albuquerque, NM 87185-0601 USA

8:00 AM, Z1 *Invited

Surfactant Effects on Ordering in GaInP Grown by OMVPE: Gerald B. Stringfellow¹; ¹University of Utah, College of Eng., 1495 East 100 S., Salt Lake City, UT 84112 USA

CuPt ordering in III/V semiconductor alloys is significant because of the dependence of bandgap energy, as well as other optical and electrical properties, on the degree of order. This paper presents the results of recent experimental studies of the effects of surfactants isoelectronic with P on ordering in GaInP grown by organometallic vapor phase epitaxy. Each of the three surfactants studied, As, Sb, and Bi, is found to result in disordering for layers grown using conditions that would otherwise produce highly ordered materials. The amount of surfactant required in the vapor phase (as the organometallic precursors TMAs, TESb, and TMBi) increases as the volatility of the group V element increases: The amount of TEAs required to produce disordered GaInP is approximately two orders of magnitude greater than for TMBi. For Sb, the most extensively studied surfactant, surface photo absorption (SPA) results indicate that disordering is caused by a replacement of [1-10] P dimers on the nominally (001) surface by Sb dimers with the same orientation. The Sb incorporation in the solid is measured using SIMS to be approximately 10¹⁸ cm⁻³. At higher Sb concentrations in the vapor, a triple-period ordered structure is formed. This coincides with a distinct change in the surface reconstruction as indicated by SPA spectroscopy. Modulation of the TESb flow rate during growth was used to produce an abrupt order/disorder heterostructure with a bandgap energy difference of 135 meV with no significant change in solid composition at the interface. The SPA results show that addition of As during growth also reduces the degree of order by displacing some of the [1-10] P dimers on the surface. In this case, significant As concentrations in the solid of a few percent are observed. Thus, As is not an effective surfactant. When TMBi is added during growth, a change in the surface reconstruction, as indicated by SPA spectroscopy, occurs for Bi concentrations producing disordered GaInP. However, the Bi also causes a marked change in the step structure with an onset that coincides with the loss of order. For singular (001) substrates, island formation is suppressed by Bi, resulting in the growth of much smoother layers. Modulation of the TMBi concentration during growth has been used to produce disorder/order heterostructures. The use of isoelectronic surfactants during growth to control the properties of a semiconducting solid is a new and exciting development in control of the OMVPE growth process. It is expected that the use of isoelectronic surfactants to control the surface reconstruction will give a powerful new tool for controlling the OMVPE processes occurring at the surface during growth.

8:40 AM, Z2

Effects of Layer Thickness Fluctuations in Ordered GaInP₂ Alloys: Su-Huai Wei¹; T. Mattila¹; Alex Zunger¹; ¹National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

Surface-reconstruction-induced ordering of (001)-grown GaInP₂ alloy is manifested by alternate monolayer superlattices Ga-In-Ga-In... oriented along [111] or equivalent directions. This spontaneous ordering reduces the band gap relative to the random alloy and splits the valence band maximum, leading to polarized excitonic transitions E_X. It has been known for a long time that 20-50 meV below this excitonic line there exist low-energy (LE) transitions E_{LE} with peculiar properties such as a long photoluminescence (PL) decay time, linear energy dependence as a function of external magnetic field, and extremely sharp emission lines (~1 meV). However, the identity of the atomic microstructure that leads to the E_{LE} transitions has been a puzzle for many years. We have studied the electronic consequences of layer thickness fluctuations in CuPt-ordered GaInP₂ alloy using plane-wave pseudopotential calculations. We show that the formation of a "sequentially mutated" Ga-In-In-Ga... region creates a hole state h1 localized in the In-In double layer, while the lowest electron state e1 is localized in the CuPt region. Thus, the system exhibits electron-hole charge separation (the e1-h1 transition is spatially indirect) in addition to spatial localization. This physical picture is preserved when the dimension of the mutated segment is reduced from 2D to 0D, resulting in disk-like dot structures. Using the calculated results we have explained the long-standing puzzle of the origin of the peculiar luminescence properties observed in ordered GaInP₂.

9:00 AM, Z3

Improvement of Electrical Characteristics of n-InGaP/n-GaAs Heterointerface using Sb Doping Grown by LP-MOVPE: *Toshihide Kikkawa*¹; Takeshi Nishioka²; Hitoshi Tanaka²; ¹Fujitsu Laboratories Limited, Comp. Semiconduct. LSI's Lab., and ECE Dept., UCSD, 9500 Gilman Dr., La Jolla, CA 92093-0407 USA; ²Fujitsu Laboratories Limited, Comp. Semiconduct. LSI's Lab., 10-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0197 Japan

Controlling InGaP/GaAs heterointerface grown by MOVPE is important for obtaining higher performance of InGaP-based HEMTs and HBTs. We recently reported that electron depletion occurred at the interface from ordered n-InGaP to n-GaAs and electron accumulation occurred at the interface from n-GaAs to ordered n-InGaP [1]. Controlling As/P exchange at the interface by modifying growth sequence or inserting growth interruption never affected electrical characteristics. Inserting intermixing layers of InGaAsP, InP, or GaP never influenced electrical characteristics, but affected only optical characteristics. We found that electrical characteristics are mainly attributed to spontaneous ordering of InGaP. When disordered-InGaP was grown on ordered-InGaP, electron depletion was observed, that verifies that electron depletion is not originated from As-containing layer around the interface. Moreover, when weakly ordered InGaP was grown at the same growth temperature for highly ordered-InGaP, electron depletion was suppressed without changing growth parameter around the interface, that proves that electron depletion is not attributed to growth temperature. In this paper, we studied the method to improve the electrical characteristics using highly ordered-InGaP without changing growth temperature. We found that Sb doping to n-InGaP improved electrical characteristics at the interface of InGaP/GaAs. We used reduced pressure horizontal MOVPE reactor capable of growing a 4-inch wafer per run. TEGa, TMin, TMSb, AsH₃, PH₃, and Si₂H₆ are used. We grew Sb-doped InGaP at the same growth temperature to grow highly ordered InGaP around 640-700°C. V/III ratios of InGaP and GaAs were 400 and 5. Growth pressure was 100hPa. Using SIMS, Sb concentration was an order of 1e18-1e20 cm⁻³. Using C-V method, we observed normal peak and valley profile of electron concentration. Prof.Stringfellow's group reported that InGaP:Sb is disordered [2]. In this study, InGaP was still ordered by PL measurements, which suggests that electrical characteristics of InGaP/GaAs interface can be altered only using Sb-doping without changing growth parameters. As increasing growth temperature without changing TMSb flow rate, Sb concentration decreased with activation energy of 1.2eV and electrical characteristics at the interface became to that without Sb doping. We propose that electron depletion and accumulation should be attributed to Ga or In vacancy around the interface due to the strain of interface observed by TEM. When Sb is doped, strain due to ordering is compensated, forming perfect electrical characteristics. Strain-related piezoelectric effects and spontaneous polarization of AlGaN result in electron depletion and accumulation characteristics at AlGaN/GaN interface. Thus, the piezoelectric effects of ordered-InGaP should be considered in the

future to explain the electrical characteristics of strain compensated Sb-doped ordered-InGaP/GaAs interface [3]. [1] T. Kikkawa et al., Inter. Symposium Compound Semiconductor (1996), Inst. Phys.Conf. Ser. No.155 (1997) 877. [2] R.T. Lee et al., Late News of EMC (1999). [3] S. Froyen et al., Appl. Phys. Lett. 68 (1996) 2852.

9:20 AM, Z4 +

The Use of a Surfactant (Sb) to Induce Triple Period Ordering in GaInP: *Christopher M. Fetzer*¹; Rung Ting Lee²; J. Kevin Shurtleff¹; G. B. Stringfellow¹; Sang Moon Lee²; T. Y. Seong²; ¹University of Utah, Depts. of Matls. Sci. and Eng., 122 S. Central Campus Dr., EMRO, Rm. 304, Salt Lake City, UT 84112-0560 USA; ²Kwanju Institute of Science and Technology, Kwanju 500-712 Korea

For the first time a surfactant is used to induce an ordered structure in an epitaxial layer. The addition of small amounts of triethylantimony (TESb) during the organometallic vapor phase epitaxy (OMVPE) growth of GaInP lattice matched to (001) GaAs substrates is shown to remove CuPt ordering with a resultant increase in bandgap energy. Increasing the concentration of Sb in the vapor beyond a critical Sb to P ratio (Sb/P(v)) of 4x10⁻⁴ gives a reversal of this behavior. The bandgap energy is observed to decrease by 50 meV at a concentration of Sb/P(v)=1.6 x 10⁻³, coincident with the formation of an ordered phase with a period triple the normal lattice spacing along the [111] and [-1-11] directions (A variant). This ordered phase has never been observed before in the GaInP alloy system or in material grown by OMVPE. The formation of the new ordered structure is believed to be related to high concentrations of Sb on the surface, which leads to a change in the surface reconstruction from (2x4)-like to (2x3)-like, as indicated by surface photoabsorption (SPA) performed in situ. Triple period ordered (TPO) material produced in this manner shows highly polarized luminescence. CuPt-B ordered material typically shows an anisotropy in the luminescence, with the PL intensity along the [110] stronger than that along the [-110] direction. The orientation of this anisotropy is due to the B variant of ordering and the induced valence band spitting.¹ Since TPO material is an A variant one would expect a reversal in this anisotropy, with the [-110] direction becoming the dominant intensity. The [-110] orientation is observed to become 41 times stronger than the perpendicular orientation. This magnitude of anisotropy is 25 times stronger than any previously observed in CuPt-B ordered GaInP.² The anisotropy is further characterized by following the PL against increases in temperature and incident laser intensity. The TPO material is also examined by photo-reflectance (PR) to deduce the radiative process responsible for the extremely polarized luminescence. References: [1] S. H. Wei and A. Zunger, Phys Rev. B 49, 14337 (1994) [2] Y. Zhang, A. Mascarenhas, S. P. Ahrenkiel, D. J. Friedman, J. F. Geisz, J. M. Olson, Solid State Commun. 109, 99 (1999).

9:40 AM Break

10:20 AM, Z5 *Invited

X-Ray Diffraction Studies of Ordering in Epitaxial ZnSnP₂: *S. Francoeur*¹; G. A. Seryogin²; S. A. Nikishin²; H. Temkin²; ¹National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA; ²Texas Tech University, Elect. Eng. Dept., Lubbock, TX 79409 USA

High-resolution x-ray diffraction is used to identify the crystallographic structure and to determine the degree of ordering in partially ordered epitaxial layers of ZnSnP₂ grown on GaAs. The natural distribution of Zn and Sn atoms in the cation sublattice is generally ordered and bulk ZnSnP₂ usually has the chalcopyrite structure (I⁴2d). However, even when energetic considerations favor the ordered structure, epitaxial growth of ZnSnP₂ always results in partially ordered or completely disordered layers with the sphalerite structure (F⁴3m). Fine changes in the growth conditions of ZnSnP₂ strongly influence the degree of ordering. Therefore, a reliable characterization method providing quantitative information on the degree of ordering is essential. We show that x-ray diffraction is well suited for both the identification of the crystallographic structure and the measurement of the order parameter. The identification of the chalcopyrite structure is based on the observation of several characteristic reflections identifying its lower symmetry, when compared to sphalerite. The order parameter can be determined quantitatively using the measured and calculated reflection intensities from a set of carefully chosen reflections. The calculated diffraction patterns are obtained from the dynamical theory of x-ray diffraction. Extinction effects and effects caused by the presence of anti-phase domain boundaries are discussed.

Epitaxial layers with order parameters varying from 0 to 30% were obtained.

11:00 AM, Z6 +

Polarization Dependent Electro-Absorption Measurements—A Powerful Tool to Study Ordering Induced Changes of the Electronic Band Structure of InGaAs: *Jochen Spieler*¹; Peter Velling²; Thomas Kippenberg¹; Peter Kiesel¹; Alexandra Lese¹; Moritz Müller¹; Werner Prost²; F. J. Tegude²; Gottfried H. Döhler¹; ¹Friedrich-Alexander University Erlangen-Nürnberg, Institut. for Tech. Phys. I, Erwin-Rommel-Str. 1, Erlangen D-91058 Germany; ²Gerhard-Mercator-University Duisburg, Solid-State Elect. Dept., Lotharstraße 65, ZHO, Gebäude LT, Duisburg D-47057 11Germany

Under appropriate MOVPE growth conditions the crystal structure of InGaAs (like of many other ternary and quaternary III-V semiconductor alloys) changes from a disordered (ZnS-structure) to a spontaneously ordered phase (superlattice in $[111]_B$ crystal directions, $CuPt_B$ -type). The drastic changes of the electronic and optical properties induced by the different crystal symmetry can be tuned with the choice of substrate orientation and growth parameters. Our investigations elucidate these dependences for InGaAs. While the principle behavior of InGaAs correlates largely with theoretical predictions and results found for GaInP by other groups, samples grown at extremely low temperatures or on differently oriented substrates show unexpected features. The latter can only be explained by an extension of current simple growth and ordering models. Multiple series of samples consisting of a 700nm thick InGaAs layer grown lattice matched on InP substrate and covered with a 50nm thick InP cap layer were realized. Using two different sets of growth parameters for the epitaxy of the InGaAs layers (carrier gas H_2 (N_2), V:III ratio 50:1 (3:1), and growth rate $1.2\mu m$ ($0.5\mu m$), respectively) we varied the growth temperature from $650^\circ C$ down to $450^\circ C$. The substrate orientation was altered as well (exactly oriented, and tilted towards $[111]_A$ or $[111]_B$). Electro-absorption measurements represent an excellent tool to determine accurately the relative energetic positions of multiple valence and conduction bands at the Γ -point. They also allow to quantify the effects of ordering on the electronic band structure and polarization anisotropy even far above the band gap energy. To carry out such measurements we deposited interdigital Schottky contacts on the grown samples. InGaAs grown at high ($>600^\circ C$) and low ($500^\circ C$) substrate temperatures appears to be almost disordered. Yet, samples grown under H_2 atmosphere on exactly oriented substrates show a strong band gap reduction and polarization anisotropy for medium ($550^\circ C$) and, surprisingly, also for extremely low growth temperatures ($450^\circ C$). Using substrates tilted towards one of the $[111]_B$ directions still can enhance these effects (optimum for 2° tilt). In contrast to the general opinion that $[111]_A$ ($[111]_B$) tilted substrate suppresses (enhances) the formation of ordering, most recent investigations on samples grown with a lower V:III ratio and growth rate under N_2 atmosphere show that also the opposite can be observed. We also present, for the first time, experimental data on the influence of ordering in InGaAs on electronic states in more distant bands. While the split-off valence band is almost unaffected the conduction band exhibits new bands folded back from the Λ and Σ direction. Measurements of the relative intensities of optical transitions into these bands and their energetic positions reveal fingerprints of different ordering variants and the domain structure in InGaAs.

11:20 AM, Z7

Investigation of Ordering in AlGaN Alloys: *Eleftherios Iliopoulos*¹; Karl F. Ludwig²; Theodore D. Moustakas¹; ¹Boston University, E.C.E. Dept., 8 St. Mary's St., Boston, MA 02215 USA; ²Boston University, Phys. Dept., 590 Commonwealth Ave., Boston, MA 02215 USA

Compositional and spatial inhomogeneities in III-nitride alloys were found to play a significant role in determining the physical properties as well as device performance and stability in this class of materials(1). The origin of such inhomogeneities was attributed either to phase separation or long range atomic ordering (2,3). In this paper we address issues related to growth and characterization of ordered AlGaN alloys. The films are grown on (0001) sapphire substrates by plasma assisted MBE and characterized by studying their structure using XRD and Raman spectroscopy and their optical properties by transmission, photoconductivity and cathodoluminescence measurements. A number of kinetic factors influencing ordering such as the ratio of III/V fluxes, growth rate, substrate temperature and doping were investigated. The strong dependence of

ordering in III/V ratio is attributed to the effect of active nitrogen species on the surface diffusion of group III adatoms. The dependence of ordering on growth rate suggests that ordering occurs in the surface as recently proposed by Northrup and co-workers (4). Ordering was found to affect the optoelectronic properties. For example the $\mu^*\tau$ product of n-AlGaN alloys with 50% Al increases significantly upon ordering. Those results as well as the mechanism of ordering in these alloys would be discussed. (1) S.Chichibu et al., APL 70, 2822 (1997). (2) D.Doppalapudi et al., JAP 84, 1389 (1998). (3) D.Korakakis et al., APL 71, 72 (1997). (4) J.E.Northrup et al., APL 74, 2319 (1999).

11:40 AM, Z8 *Invited

Spatial High Resolution Photoluminescence Study of Intrinsic and Self-Assembled Quantum Dots: *M. Wenderoth*¹; P. G. Blome¹; U. Kops¹; M. Hübner¹; E. Spiecker¹; R. G. Ulbrich¹; C. Geng²; J. Porsche²; F. Scholz²; ¹Universität Göttingen, IV. Physikalisches Institut., Bunsenstr. 13, Göttingen 37073 Germany; ²Universität Stuttgart, 4 Physikalisches Institut, Pfaffenwaldring 57, Stuttgart 70550 Germany

A great variety of quantum dot (QD) systems has been fabricated by different techniques. In this talk we will discuss two types of QD's both embedded in (GaIn)P. While the first class-InP-QD's grown in the Stranski-Krastanov (SK) mode on the (001) surface-are intentionally made, the second type is naturally created by alloy fluctuations in a partially ordered GaInP bulk crystal forming anti phase boundaries running along the (111) order planes. We call this second class intrinsic QD's. We have investigated both type of QD by means of spatial high resolution photoluminescence with 500 nm lateral resolution. First, individual MOVPE-grown self-assembled InP quantum dots in a (GaIn)P matrix are investigated. We observed an abrupt change from the well known but yet unclear relatively broad emission band at low temperature to narrow line at $T > 45K$. The high temperature mode is the one expected for a fully confined quantum system. The up to now not understood broad single dot PL at low temperatures of this material system can be explained by a spectral diffusion model that takes the fluctuating charge configurations into account, which are surrounding the quantum dots and interact with its groundstate via Coulomb interaction. From the PL measurements we conclude that the interacting carriers are most probably located due to thickness fluctuations in the wetting layer. Their release at higher temperatures, indicated by the disappearance of the corresponding PL signal at the same threshold temperature $T=45K$, removes the perturbation leading the appearance of single dot spectra. A simple model taking Coulomb interaction into account can fit our data satisfactory. Second, the intrinsic QD are observed in single-variant, partially ordered (GaIn)P bulk samples grown by MOVPE with substrate misorientation of 6° towards $[111]_B$ directions. In the energy region of the well-known, ordering-induced low energy emission band (LE) we resolve narrow optical transitions with a linewidth of only 0.3-1 meV and the following spectroscopic properties: (i) no thermal broadening in the temperature range 0-3-60 K, (ii) a diamagnetic shift with pronounced spatial anisotropy parallel and perpendicular to the $[111]_B$ direction, (iii) linear Zeeman-splitting in magnetic fields 0-12 T, and (iv) growth and saturation of biexcitonic satellite lines for increasing excitation power 0.1-100 μW . We demonstrate that the transition are connected with intrinsic quasi zero-dimensional electron-hole confinement formed at the anti-phase-boundaries in the crystal.

Session AA. Novel Materials

Friday AM Room: Lindsey Auditorium
June 23, 2000 Location: Sturm Hall

Session Chair: Robert N. Sacks, Ohio State University,
EE Dept., Columbus, OH 43210-1272 USA

8:00 AM, AA1

BGaInAs Alloys Lattice Matched to GaAs: *John F. Geisz*¹; Daniel J. Friedman¹; Jerry M. Olson¹; Sarah R. Kurtz¹; Robert C. Reedy¹; Amy B.

Swartzlander¹; Brian M. Keyes¹; Andrew G. Norman¹; ¹National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

We demonstrate that direct gap $B_xGa_{1-x}In_yAs$ alloys can be grown lattice-matched to GaAs with band gaps below that of GaAs. Such alloys have potential applications in high efficiency solar cell and laser devices. We report the epitaxial growth of zinc-blende $B_xGa_{1-x}In_yAs$ and $B_xGa_{1-x}As$ on GaAs substrates with boron concentrations (x) up to 2%-4% by atmospheric-pressure metal-organic chemical-vapor deposition using diborane, triethylgallium, trimethylindium, and arsine sources. These layers were obtained only within a narrow range of growth conditions. The elemental, structural, and optical properties of these boron-containing alloys were determined by secondary-ion mass spectroscopy, auger electron spectroscopy, double-crystal X-ray diffraction, transmission electron microscopy (TEM), photoluminescence, electrochemical spectral response, and optical transmission measurements. We show that the band gap of $B_xGa_{1-x}As$ increases by only 4-8 meV/%B with increasing boron concentration in the concentration range up to 2-4% boron. Such small differences in the band gap from that of the substrate GaAs require great care in the determination of the band gap. Based on theoretical predictions of the BAs direct gap, these results indicate a band gap bowing parameter of approximately 2 eV. This bowing is considerably less than the bowing observed in the GaN_xAs_{1-x} system, but closer to the bowing parameters observed in more traditional III-V alloy systems. We also demonstrate an epitaxial $B_xGa_{1-x}In_yAs$ layer nearly lattice-matched to GaAs with a band gap of 1.34 eV that exhibits zinc-blende diffraction spots by TEM, strong band-edge luminescence, good photocurrent, and low background carrier concentration.

8:20 AM, AA2

Growth of Homogeneous GaAsGe Alloys by Kinetic Stabilization: *Andrew Gordon Norman*¹; Jerry M. Olson¹; Mowafak M. Al-Jassim¹; ¹National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401-3393 USA

$(GaAs)_{1-x}(Ge_2)_x$ alloys, that are lattice-matched to GaAs, are a candidate material to provide a direct band gap of 1 eV for improved-efficiency multi-junction solar cells. Previous work [1,2] has indicated that $(GaAs)_{1-x}(Ge_2)_x$ layers, $0 \leq x \leq 0.22$, grown by metal organic vapor phase epitaxy (MOVPE) at temperatures between 640° and 690°C exhibit phase separation into GaAs-rich zinc-blende regions and Ge-rich diamond cubic regions. At a growth temperature of 640°C the Ge-rich regions are segregated on {115}B planes. At 690°C and above the Ge-rich regions form large platelets lying on (001), parallel to the growth surface. In this work we demonstrate that single-phase homogeneous $(GaAs)_{1-x}(Ge_2)_x$ layers may be obtained by MOVPE growth at lower temperatures (600°C) and higher growth rates ($\geq 0.1\mu\text{m}$ per minute). Under these growth conditions the phase separation, that occurs at the surface of the growing layers, is kinetically prevented, resulting in relatively homogeneous $(GaAs)_{1-x}(Ge_2)_x$ layers. The use of a triethyl-gallium source in place of a trimethyl-gallium source may also be beneficial in obtaining single-phase alloys. We will also report initial results on the MOVPE growth of $(Ga_{0.52}In_{0.48}P)_{1-x}(Ge_2)_x$ alloy layers.

8:40 AM, AA3 +

Highly Doped InAlP:Mg Grown by Metalorganic Chemical Vapor Deposition: Yuichi Sasajima¹; *Min-Soo Noh*¹; Richard D. Heller¹; Russell D. Dupuis¹; ¹The Sumitomo Chemical Company Limited, Tsukuba Rsch. Lab., 6 Kitahara, Tsukuba, Ibaraki 300-3294 Japan

We have studied the growth of heavily Mg-doped InAlP by MOCVD, and the influence of the growth rate and the lower layer doping on the hole concentration in the subsequently grown InAlP:Mg film. The maximum free-hole concentration in InAlP is strongly dependent upon the growth parameters, particularly the temperature, and has been reported to be $p_{\text{max}} \sim 1 \times 10^{18} \text{ cm}^{-3}$ for Zn-doped InAlP and Mg-doped InAlP (InAlP:Mg) grown by MOCVD. We have obtained $p_{\text{max}} \sim 3.9 \times 10^{18} \text{ cm}^{-3}$ for ex-situ annealed InAlP:Mg films. This value is, to our knowledge, the highest reported for MOCVD-grown InAlP and is as high as has been reported for InAlP:Be grown by gas-source MBE at low temperatures, i.e., $p_{\text{max}} = 3.5 \sim 4.2 \times 10^{18} \text{ cm}^{-3}$. The InAlP:Mg samples were grown by low-pressure MOCVD, using an EMCORE GS3200 UTM reactor. The growth temperature and pressure were 650°C and 60 Torr, respectively. Adduct-grade trimethylindium, solution trimethylindium, and trimethylaluminum, and high-purity PH_3 were used as sources, and bis(cyclopentadienyl)magnesium and disilane were employed as dopants. The V/III ratio was ~ 560 .

Two growth rates for InAlP:Mg were employed in this work: a “low growth rate” $\sim 15\text{nm}/\text{min}$ and a “high growth rate” $\sim 25\text{nm}/\text{min}$. Typically, three doped InAlP layers were grown sequentially, a “buffer” layer, a “lower” Mg-doped layer, and an “upper” Mg-doped layer. The [Mg] was determined by SIMS and the hole concentration was measured using an electrochemical profiler. Our study shows that the Mg incorporation is drastically dependent upon the InAlP growth rate (at a constant V/III ratio). Furthermore, we examined the influence of the lower layer doping upon the p values of InAlP:Mg, and we found that p in InAlP:Mg increases with increasing carrier concentration in the InAlP layer grown just prior to the Mg-doped layer. We believe that the suppression of Mg-diffusion from the layer is related to the increase in p in InAlP:Mg grown on InAlP with high carrier concentrations. The Si_2H_6 or Cp_2Mg dopant flow during the growth of the “lower layer” of InAlP was changed while keeping the Cp_2Mg flows constant in the “upper” InAlP:Mg layers. We have obtained higher p in InAlP:Mg grown on the InAlP:Si layer with higher n and also on the InAlP:Mg layer with higher p. However, for the InAlP:Mg on InAlP:Si, the value of p saturates for $n \sim 1 \times 10^{18} \text{ cm}^{-3}$, while the p in InAlP:Mg on InAlP:Mg is observed to increase even when the lower layer has $p \sim 4 \times 10^{18} \text{ cm}^{-3}$. We propose that suppression of the Mg out-diffusion into InAlP:Si is another possible reason why we have achieved higher p in InAlP:Mg grown on heavily doped InAlP:Si. We speculate that the heavily doped InAlP:Si layer functions as a barrier to prevent Mg-diffusion from InAlP:Mg. Thus, the InAlP:Si layer forces the Mg dopant atoms to be confined in the InAlP:Mg layer.

9:00 AM, AA4 +

Effects of Substrate Offset Angles on MBE Growth of ZnO (II): *Keiichiro Sakurai*¹; Ryo Tatsumi¹; Takeshi Kubo¹; Ken Nakahara²; Tetsuhiro Tanabe²; Shizuo Fujita¹; Shigeo Fujita¹; ¹Kyoto University, Depts. of Elect. Sci. and Eng, Yoshida-Honmachi, Sakyo, Kyoto 606-8501 Japan; ²Rohm Company Limited, Opt. Devices Rsch and Dev. Div., 21, Mizosaki-tyo, Saiin, Ukyo, Kyoto 615-8585 Japan

Recently, ZnO is considered as a promising new material for short-wavelength light emitting/receiving semiconductor devices. In order to fully utilize its excitonic properties in future light devices, the crystallinity and morphology of the films are required to be higher than ever. However, the film quality largely depends on the configuration of the heterointerface between ZnO and the widely used sapphire substrates, such as the slight off-angle of the substrate, or the buffer layer growth prior to the main layer growth. Our group has been concentrating on taking control of the ZnO/sapphire interface. Previously, we have found that an off-angle of 0.2-2.8° of c-plane sapphire may greatly enhance the morphology of grown ZnO films. In this work, we have made further investigations considering the effect of off-angles, especially focusing on effects combined with other growth conditions. ZnO films were grown on c-plane or a-plane sapphire substrates with various off-angles, using an Eiko EW-100 water-cooled MBE system, RF plasma oxygen cell, metal Zn evaporated from a K-cell. Growth temperature was 600-700°, oxygen flow rate was 0.2-0.5 sccm, Zn pressure measured at substrate position was $5e-7$ to $1e-6$ Torr. On c-plane sapphire substrate, the morphology of the ZnO films could be enhanced with typical off-angles to the a-axis direction, but the effect was weaker when the substrate was tilted to the m-axis direction up to 2.0°. On c-plane just oriented substrates, the same effect was observed by adjusting the oxygen flow and Zn flux. These results strongly suggest that the effects of off-angles are deeply combined with other growth parameters. Details would be presented at the conference site. The case of off-angled a-plane sapphire, which is recently being introduced for ZnO epitaxy, would also be discussed.

9:20 AM, AA5 Late News

9:40 AM Break

Session BB. Advances in the Growth of Quantum Dots

Friday AM Room: Lindsey Auditorium
June 23, 2000 Location: Sturm Hall

Session Chairs: Art Gossard, University of California, Dept. of Matls. Sci. and Eng., Santa Barbara, CA 93106 USA; Brian Bennett, Naval Research Laboratory, Elect. Matls. Brnch., Washington, DC 20375-5347 USA

10:20 AM, BB1

Methods for Ordering Self-Assembled InAs/GaAs Quantum Dots: *Hao Lee*¹; Jo A. Johnson¹; James S. Speck¹; Pierre M. Petroff¹; ¹University of California, Matls. Dept., Santa Barbara, CA 93106 USA

Quantum dot (QD) structures have been extensively studied in the last several years because of their unique optical, electronic and magnetic properties. Strain induced island formation in the Stranski-Krastanow growth mode for lattice mismatched systems, such as InAs/GaAs, provides an efficient method for producing quantum dots. However, islands, which are formed spontaneously in this growth mode, exhibit large size and density fluctuations and random nucleation. The lack of control on the island formation, especially the island positioning, poses a great hurdle to the incorporation of QDs into devices. To control the island nucleation, we developed an experimental approach that combines lithography with self-assembly. In this method, we control the island formation by growing on prepatterned substrates. We investigated the InAs/GaAs coherent island system grown by molecular beam epitaxy. A GaAs (100) substrate is first patterned using holography to obtain mesa arrays over larger areas. Square mesas, with base dimensions of 100nm to 300nm are easily fabricated by chemical etching. InAs islands are deposited following the growth of a thin GaAs buffer layer in our MBE chamber. Ordered InAs islands are grown in two distinct methods. In the first, islands are deposited directly on top of the GaAs buffer layer. InAs islands are all formed in between mesas and by carefully choosing the buffer layer thickness, partial order among islands can be observed by atomic force microscopy (AFM). In the second method, an InGaAs strained layer, which acts as stressor layer, is incorporated in the GaAs buffer layer before a second InAs deposition on the GaAs. For stressor layers above a critical layer thickness, most islands are formed on top of mesas. Long range ordering of islands formed on top of mesas is statistically analyzed and shown to be better than 90%. As we vary the mesas dimension and orientation, control of island ordering was achieved. We will present AFM images of ordered InAs islands and the associated photoluminescence spectra from ordered QDs arrays. We will discuss the possible nucleation processes, which could be responsible if equilibrium thermodynamics are dominant. This work is supported by AFOSR and ARO.

10:40 AM, BB2

Optical, Structural, and Electrical Properties of Close-Packed Arrays of InP Quantum Dots: *Olga I. Micic*¹; S. P. Ahrenkiel¹; Arthur J. Nozik¹; ¹National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80033 USA

Successful fabrication of close-packed arrays of colloidal InP quantum dots (QDs) with diameters ranging from 30 to 90 Å has been achieved. In close-packed solid films of InP QDs, we found efficient long-range energy transfer. The electron exchange mechanism, which occurs at a short distance (10-15 Å), is not applicable for our system. In our experiments, the critical separation distance for energy transfer was found to be about 80 Å. In this close-packed array, the energy transport is more favorable than electron transport. Extremely small electrical conductivity in close-packed arrays of InP QDs capped with organic stabilizer was found; the close-packed films behave as insulators. However, we found reasonably large conductivity when the close-packed solid was built with very small QDs that were prepared in the absence of organic nonvolatile stabilizers (broad size distribution), and that are free of capping groups in solid films. It seems that the main reason for the small conductivity in the film with

dots capped with the organic stabilizer that decomposes with heating is the large barrier height and small overlap integral values between neighboring QDs. We also tried to vary the barrier height of InP QDs to increase overlap integral values between neighboring QDs and enhance electron delocalization over the entire QD by preparation (InP)ZnCdSe₂ core/shell QDs. Our results show that lattice matching permits epitaxial growth of the ZnCdSe₂ shell on InP QDs, and shells of up to fifteen monolayers in thickness were grown on a core InP QD with a diameter of 30 Å. An added important advantage results from differences in the confinement of electrons and holes in this system. Shell growth was consistently accompanied by a red shift of the absorption and emission spectra because the electron is delocalized over the entire QD whereas the hole is localized within the core.

11:00 AM, BB3 +

Electronic Structure Of Self-Limited InAs/GaAs Quantum Dots Grown Via Punctuated Island Growth Approach: *Ildar Mukhamet-zhanov*¹; Robert Heitz¹; Anupam Madhukar¹; ¹University of Southern California, Dept. of Matls. Sci. and Phys., 3651 Watt Way, VHE 514, Los Angeles, CA 90089-0241 USA

Punctuated island growth (PIG) approach has allowed significant control on density, size and shape distribution of strain-driven InAs/GaAs epitaxial three-dimensional island quantum dots (QDs). Island size distributions have revealed QD shape change to steeper sidewalls with increasing island volume at a self-limited island base size, driven by slow kinetics of adatom incorporation near high stress base edge regions. Such self-limited QDs have a base size ~18nm and a height ~9nm, suggestive of pyramidal shape with {011} type facets. Dramatic improvement in the QD uniformity with typical PL (photoluminescence) linewidths ≤25meV achieved via PIG approach has allowed observation of phonon replica emission and thus extraction of the exciton-phonon coupling in epitaxial island QDs (Huang-Rhys factor S~0.02). Here, we report on electronic structure of such PIG QDs. High excitation density non-resonant PL, resonant PL, and ground state PLE (PL excitation) are employed to investigate ground state and excited state transitions for QD samples with such narrow size distribution. For 3ML total InAs deposition, at low temperatures (T=6K) the ground state transition is at 1.06eV and the dominant excited electron (hole) states are 59 and 109meV (26 and 58meV) above the QD ground state. Shifts in PLE peak positions with varying detection energy are observed, consistent with the quantum size effect of increase in excited states energies for smaller dots. Temperature-dependent PL indicates hole emission into the wetting layer state (ΔE~110meV) and exciton emission into the GaAs (ΔE~430meV) to be the major effects for quenching of PL with increase in temperature. PL linewidth increase from 25meV to 29meV with increasing temperature suggests carrier localization to be deep enough as to inhibit formation of a common Fermi-level even up to room temperature. The temperature dependence of the ground state transition shows the first excited state transition to be very close (~3-5meV) to the ground state transition of the QD. These results, provided for well characterized quantum dots, serve as a test bed for theoretical models and approaches and can be used to assess their relative strengths.

11:20 AM, BB4 +

Evolution and Dissociation of InAs/InP Quantum Dots during Growth Interruption: *Sukho Yoon*¹; Heedon Hwang¹; Kwang-Sik Cho¹; Euijoon Yoon¹; Hyeonsik Michael Cheong²; ¹Seoul National University, Sch. of Matls. Sci. and Eng., ISRC SNU Shillim-Dong San 56-1, Kwanak-Gu, Seoul 151-742 Korea; ²Sogang University, Dept. of Phys., Seoul 121-742 Korea

The self-assembled quantum dots (SAQDs) are promising for high-performance electronic and optical devices. Growth interruption (GI) process was intentionally given before the quantum dots (QDs) were capped with barrier materials to tailor the dot properties in In_xGa_{1-x}As/GaAs systems. It was reported that the material transport from the wetting layer (WL) and/or by the island decomposition during GI affected the evolution of SAQD, resulting in the changes in optical properties. Although the InAs/InP QD is promising for optoelectronic devices covering 1.3-2 μm range, the detailed information on QD evolution during GI is still lacking. Recently, we observed that the excess InAs formation was caused by the As/P exchange reaction and subsequent strain-driven In migration. Therefore, it is very likely that the As/P exchange reaction may affect the evolution of InAs/InP QDs during GI, consequently opti-

cal properties of QDs. In this study, we present the development and dissociation processes of InAs SAQDs on InP during GI at various GI sequences with different atmospheres and times. The QDs were characterized by photoluminescence (PL) and high-resolution transmission electron microscope (TEM). It was found that the GI could tailor the optical and structural properties of QDs. Moreover, the in situ, real-time spectral reflectance monitoring during QD formation clearly showed the differences in QD evolution behavior. The InAs/InP SAQD sample capped with InP after 2-sec GI under AsH₃ atmosphere showed a few PL peaks other than a QD peak at 0.820 eV, presumably from the thickness fluctuation of the wetting layer before the complete evolution to quantum dots. However, the fully developed InAs/InP SAQD sample with 30-sec GI under AsH₃ flow rate of 5.2 sccm showed a PL peak at 0.728 eV at 21K. Also, the PL peak from the sample with GI under 52 sccm AsH₃ flow rate shifted to 0.640 eV, showing the average size of QDs increased by GI under higher AsH₃ pressure. It suggests that the QD evolution is strongly influenced by AsH₃ partial pressure. On the contrary, when the GI was introduced under PH₃ atmosphere for 10-sec after the 30-sec GI at 52 sccm AsH₃ flow rate, the PL peak position shifted to the higher energy of 0.677 eV. The blue shift after the GI under PH₃ atmosphere is presumed to be due to the dissociation of QD by the P/As exchange reaction under PH₃ atmosphere. Moreover, the 30-sec GI under PH₃ atmosphere decomposed the InAs islands drastically, resulting in quantum wells (QWs) with thickness fluctuations as confirmed by several PL emissions between 0.77 and 0.95 eV (corresponding to 4-9 monolayer thick InAs QWs). It was also observed that the GI under H₂ atmosphere froze the QD sizes and the PL peak positions did not change. It was found that the evolution and dissociation of InAs/InP QDs could be controlled and the emission wavelength of QDs could be tailored intentionally for various applications by proper control of the GI sequences with different atmospheres and times. We will also present spectral reflectance data during growth and discuss the structural and optical properties in detail.

11:40 AM, BB5 +

Growth and Characterization of InP Self-Assembled Quantum Dots on GaAs Substrates: *Jae-Hyun Ryou*¹; Russell D. Dupuis¹; C. V. Reddy²; Venkatesh Narayanamurti²; David T. Mathes³; Robert Hull³; Alexander Mintairov⁴; James L. Merz⁴; ¹The University of Texas at Austin, Microelect. Rsch. Ctr., PRC/MER-R9900, Austin, TX 78712-1100 USA; ²Harvard University, Gordon McKay Lab. of Appl. Sci., Cambridge, MA 02138 USA; ³The University of Virginia, Dept. of Matls. Sci. and Eng., Charlottesville, VA 22906 USA; ⁴University of Notre Dame, Dept. of Elect. Eng., Notre Dame, IN 46556 USA

III-Phosphide self-assembled quantum dots (SAQD or simply QD) structures offer a potential to realize injection lasers operating in the visible regions with improved performance characterizations such as low threshold current densities, high characteristic temperatures, and high differential gain. Also, SAQD growth can overcome the limitations of lattice matching between the substrate and the epitaxial active region due to the nature of the growth mode (i.e. strain-induced Stranski-Krastanow mode). In this paper, we report the growth and characterization of InP SAQDs embedded in In_{0.51}Al_{0.49}P cladding layers on GaAs substrates by metalorganic chemical vapor deposition (MOCVD) and their structural, materials, and optical characteristics. While earlier studies have employed InGaP "wetting layers", we use wide-bandgap InAlP cladding layers. The InP SAQDs are grown at temperatures in the range 475-650°C using trimethylindium and phosphine. The morphology of the exposed SAQDs (grown without the upper cladding and cap) is observed by atomic force microscopy (AFM). For a fixed 15ML of InP growth, as the growth temperature increases from 475 to 600°C, the average QD size increases, while the density decreases. For instance, the measured densities are ~0.5x10⁶ and ~1.7x10⁶ mm⁻² with QD sizes ~140 and ~50 nm for QDs grown at 550 and 500°C, respectively. For InP QDs grown at 650°C for 15ML, however, the average QD size is dramatically decreased to ~10 nm and the QD density is increased to ~1.5x10⁸ mm⁻². The growth of 15ML InP QDs at 650C is also studied on various (100) substrates with different tilt angles along <111>A, such as 0, -10, and -15°. While QD sizes and densities on on-axis and 10° off substrates are comparable, those on 15° off substrate are quite different. AFM, SEM, and Nomarski microscope examination shows low-density huge islands and small dots between islands. Low-temperature (4K) photoluminescence "plan-view" (PL) is performed to determine the light-emitting characteristics of the InP SAQDs embedded

in InAlP cladding layers. We observe relatively broad, intense emission from QDs ranging from λ~620 to λ~750nm depending on the growth conditions. Transmission electron microscopy (TEM) is employed to study the microscopic material quality of QDs. Larger QDs exhibit dislocations whereas smaller dots appear to be free of dislocations. Since the bandgap of the active InP SAQDs is modified by multi-dimensional quantum confinement, the band offsets of bulk material do not apply in QDs. Ballistic electron emission microscopy (BEEM) measurements are employed to determine the band structure and electronic states of the InP QDs. Analysis of the BEEM data shows the electronic structure of the InP QDs contains sharp electronic transitions. In summary, we will report on optical, structural, and electronic properties of InP SAQDs grown on GaAs substrates using the MOCVD epitaxial growth technique.

Session CC. Nitride Optoelectronics

Friday AM Room: Sturm Auditorium
June 23, 2000 Location: Sturm Hall

Session Chairs: Russell D. Dupuis, University of Texas, Austin, TX 78712 USA; Christian M. Wetzel, Meijo University, High Tech. Rsch. Ctr., Nagoya, 468-8502 Japan

8:00 AM, CC1

Dislocations in AlGaInN-based Laser Diodes: *Tomonori Hino*¹; Shigetaka Tomiya²; Takao Miyajima³; Katsunori Yanashima¹; Takeharu Asano¹; Satoru Kijima¹; Tsuyoshi Tojyo¹; Shiro Uchida¹; Masao Ikeda¹; ¹Sony Shiroishi Semiconductor, Inc., Devt. Ctr., 3-53-2 Shiratori, Shiroishi, Miyagi, 989-0734, Japan; ²Sony Corporation, Environ. & Anals. Tech. Dept., Tech. Sup. Ctr.; ³Sony Corporation, Semicon. Las. Div., Semicon. Co., Core-Tech. & Net. Co.

AlGaInN-based III-V epitaxial layers are commonly grown on sapphire substrates to fabricate violet-blue laser diodes (LDs) and light emitting diodes (LEDs). There is, however, a high density of threading dislocations in GaN epitaxial layers. It is well known that such dislocations act as non-radiative center in III-V arsenides and phosphides. In order to obtain high brightness, therefore, we have to reduce the dislocation density. High-brightness GaN-based LEDs have been commercialized in spite of their high dislocation density. To understand the reason for this contradiction, it is important to clarify the relationship between threading dislocations and non-radiative centers in GaN epitaxial layers. We report here the characterization of GaN epitaxial layers on a sapphire substrate by raised-pressure metalorganic chemical vapor deposition using our newly developed HCl vapor phase etching technique, scanning electron microscopy (SEM), atomic force microscopy (AFM), transmission electron microscopy (TEM), and photoluminescence (PL). Three types of etch-pits (a, b, and g type) were observed on the etched GaN surface. We clarified the relationship between etch-pits and threading dislocations (screw, mixed, and edge dislocations) using SEM, AFM, and TEM. The PL intensity increased as the total number of etch-pits corresponding to screw and mixed dislocations decreased from 2x10⁸cm⁻² to 4x10⁶cm⁻². The number of etch-pits corresponding to edge dislocations, however, did not change from approximately 3x10⁸cm⁻². We conclude, therefore, that threading dislocations with a screw-component burgers vector, which are the minority, act as strong non-radiative centers in GaN epitaxial layers. On the other hand, edge dislocations, which are the majority, do not act as strong non-radiative centers. This fact tells us that we have to reduce threading dislocations, especially, which have a screw-component burgers vector, to improve the quality of GaN-based LDs and LEDs. We fabricated GaInN/GaN/AlGaIn SCH-MQW LDs on epitaxially lateral overgrown GaN layers. The ridge-stripe was formed in the lateral growth region, which was confirmed to have a low dislocation density by TEM, with a geometry of 2.0mm x 600mm. The threshold current was 42.7mA, corresponding to a threshold current density of 3.56kA/cm² and the operating voltage at the threshold current was 4.99V at 25°C. The lifetime was more than 200hours under

CW operation with a constant power of 30mW at 50°C. We will discuss the behavior of dislocations in the stripe region for such long-lived LDs.

8:20 AM, CC2

Enhanced Light Emission from Strain-Tuned Modulation-Doped Quaternary AlInGaN/InGaN Quantum Wells: *J. Zhang*¹; M. Asif Khan¹; J. W. Yang¹; G. Simin¹; R. Gaska²; M. Shur²; ¹University of South Carolina, Dept. of Elect. and Comp. Eng., 301 S. Main St., Rm. 3A80, Columbia, SC 29208 USA; ²Sensor Electronic Technology, Inc., 21 Cavalier Way, Latham, NY 12110 USA

Recently we have demonstrated a novel Energy Band/Lattice Engineering approach using quaternary AlInGaN material system for energy band and lattice mismatch tailoring for piezoelectric doping in electronic device applications. In this paper, we demonstrate that incorporation of quaternary AlInGaN barrier into AlInGaN/InGaN QW structure enables us to nearly independently control built-in electric field and quantum confinement. We studied CW photoluminescence (PL) in the structures, which have: (i) nominally undoped InGaN QWs with different Al/In ratio in the barriers; (ii) modulation doped QWs with constant Al/In ratio in the barriers. The obtained results show that incorporation of Al into barriers results in a blue-shift of the emission peak. In contrast, increase in In molar fraction in the barriers leads to a red-shift of the peak and significant increase in emission intensity. The modulation doping of QWs results in a blue-shift of PL peak and non-monotonous change of the emission intensity. The maximum in PL signal intensity was measured at different Si concentrations determined by Al/In ratio in the barriers. We attribute this behavior to the reduction of the piezoelectric field in QWs with quaternary AlInGaN barriers and/or modulation doping. The obtained results are in a good agreement with the calculations of piezoelectric fields and overlap integrals for optical transitions. The extracted built-in electric fields for AlGaIn/InGaN with 15% of Al and 20% of In are as high as 10^6 V/cm. The incorporation of up to 15% of In in the barrier reduces the field to approximately $3\text{-}5 \times 10^5$ V/cm. The optimized modulation doping reduces the built-in field below 10^5 V/cm. Our results show that combination of Energy Band/Strain engineering with modulation doping of the structures allows smooth tuning of emission wavelength and enhancement of emission efficiency. This emission enhancement using quaternary barrier MQWs is promising for development of high-brightness LEDs for solid state lighting.

8:40 AM, CC3 +

High Performance AlGaIn and GaN Photodetectors Grown by Metalorganic Chemical Vapor Deposition: *Damien J.H. Lambert*¹; Michael M. Wong¹; Uttiya Chowdhury¹; Charles Collins¹; Bo Yang¹; Ting Li¹; Ho Ki Kwon¹; Bryan S. Shelton¹; Ting Gang Zhu¹; Joe C. Campbell¹; Russell D. Dupuis¹; ¹The University of Texas at Austin, Microelect. Rsch. Ctr., PRC/MER-R9900, Austin, TX 78712-1100 USA

We report the growth, processing, and characterization of high performance AlGaIn/GaN ultraviolet (UV) and solar-blind PIN photodetectors. Specifically, strained AlGaIn:ud and AlGaIn:Si layers $\sim 1\mu\text{m}$ thick having Al compositions as high as 50% can be grown without cracks on high-quality GaN epitaxial material, and such structures can be used to detect UV-light in the solar-blind spectral region. The heteroepitaxial structures were grown by low-pressure metalorganic chemical vapor deposition (MOCVD) in an EMCORE D125 UTM reactor on sapphire substrates. The sources employed are adduct-purified alkyls: trimethylgallium, trimethylaluminum, and bis(cyclopentadienyl)magnesium; and high-purity silane, and ammonia precursors. We have varied the growth conditions (e.g., temperature, Al to Ga ratio, pressure) and have studied the correlation of the symmetric and asymmetric X-ray diffraction linewidths, surface morphology, and thickness of the absorption layer and of the window layer upon the photodetector I-V characteristics, dark current, white-light photoresponse, and ultraviolet photoresponse. High-quality GaN layers and AlGaIn films with various alloy compositions ranging from 10% to 50% Al have been used as the absorbing layer in these structures. Some samples employed crack-free structures composed of up to $\text{Al}_x\text{Ga}_{1-x}\text{N}$ ($x \sim 0.5$) heteroepitaxial layers while others employed selectively regrown AlGaIn/GaN heterostructures. We find that for short-wavelength UV illumination, most of the incident light is absorbed within the first 100nm of material and that the quantum efficiency of the PIN devices increases as the thickness of the top n-type or p-type layer decreases. Our data show that an “n-up” PIN structure with the n-type

layer on the top exhibits improved quantum efficiency because, contrary to the case of p-type AlGaIn material, relatively high electrical conductivity and long carrier diffusion lengths can be achieved for thin n-type AlGaIn material. For some devices, a selective regrowth technique has been used with small regrowth area to enhance either the AlGaIn alloy composition or the AlGaIn total thickness of the wide-bandgap material grown on the GaN epitaxial “substrate”. The regrowth process using small-area openings in the mask presumably reduces the strain of the AlGaIn layers on “bulk” GaN material. By optimizing the buffer layer and the growth conditions (e.g., temperature, III/V ratio, pressure) we have been able to obtain high-quality $\text{Al}_x\text{Ga}_{1-x}\text{N}$ ($x \sim 0.5$) layers with a symmetric (0002) X-ray rocking curve FWHM values of 290arc-s for $\sim 1\mu\text{m}$ thick material, close to that obtained for high-quality GaN/sapphire films. Furthermore the surface atomic force microscopy (AFM) measurements on $5 \times 5\mu\text{m}$ areas show RMS roughness values of about 0.5nm for our best thick AlGaIn layers. By optimizing the growth conditions, we have achieved solar-blind UV photodetectors with quantum efficiencies as high as $\sim 13\%$ at $\lambda \sim 280\text{nm}$ with no AR coatings. Further description of our materials and device results will be made.

9:00 AM, CC4 +

UV Digital Cameras Based on 32x32 and 128x128 Arrays of AlGaIn p-i-n Photodiodes: *J. D. Brown*¹; J. Matthews¹; C. Boney¹; P. Srinivasan¹; J. F. Schetzina¹; J. D. Benson²; K. V. Dang²; Thomas Nohava³; Wei Yang³; Subash Krishnankutty³; ¹N.C. State University, Phys. Dept., P.O. Box 8202, Raleigh, NC 27695 USA; ²Night Vision and Electronic Sensors Directorate, AMSEL-RD-NV-IRT, 10221 Burbick Rd., Ste. 430, Fort Belvoir, VA 22060 USA; ³Honeywell Technology Center, 12001 State Hwy., Plymouth, MN 55441 USA

Visible-blind UV digital cameras based on 32x32 and 128x128 arrays of AlGaIn p-i-n photodiodes have been successfully developed. The nitride photodiode structures were synthesized on 2-inch diameter double-side polished sapphire substrates in a low-pressure, vertical gas flow MOVPE system that employs fast substrate rotation. Two types of diode structures were employed. The first type consists of a 1.5 μm thick n-type layer of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}:\text{Si}$ grown by MOVPE onto a low temperature AlN buffer layer on sapphire. On top of this layer is a 0.2 μm undoped GaN active layer followed by a 0.5 μm p-type GaN:Mg layer. This structure produces devices that respond to UV radiation in the 320-365 nm wavelength region when illuminated through-the-substrate. Selected test diodes displayed 300K peak responsivities as large as $R=0.21\text{A/W}$ at 360 nm, corresponding to an internal quantum efficiency of 82%. Detectivities as large as $D^*=6.1 \times 10^{13}\text{cm Hz}^{1/2}\text{W}^{-1}$ were measured at 360 nm. This is one of the largest D^* values ever obtained for any semiconductor photodetector at any wavelength and temperature, and is within a factor of six of D^* values for UV-enhanced photomultiplier tubes. The second type of diode structure studied employs a base n-type layer of $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}:\text{Si}$ onto which undoped and p-type layers of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ are deposited sequentially by MOVPE. These devices respond to UV radiation in the 280-320 nm wavelength region. Selected test diodes of this type exhibit peak responsivities $R=0.14\text{A/W}$ at 300 nm, corresponding to internal quantum efficiencies of 66%, and detectivities as large as $D^*=1.2 \times 10^{13}\text{cm Hz}^{1/2}\text{W}^{-1}$. 32x32 and 128x128 diode arrays were hybridized to Si readout integrated circuits (ROICs) using flip-chip bonding techniques in which In bump bonds were employed. The hybridized focal plane arrays (FPAs) were then wire-bonded to leadless chip carriers (LCCs) and inserted into the UV camera for testing. The UV digital camera employs an adjustable fused quartz lens for focusing the desired UV scene onto the AlGaIn FPA, together with readout and testing electronics controlled by computer. The nitride FPA image can be read out from the Si ROIC and displayed real-time at frame rates ranging from 15-240 frames per second, or a sequence of images can be stored by computer as a digital image data set from which a selected frame or sequence of frames can be used to generate digital UV images or movies. A variety of UV imagery in the 280-365 nm region has been obtained using the nitride UV camera. Single-frame visible-blind UV images of alpha-numeric scenes and geometric objects, along with digital UV movies of pulsed xenon lamps, UV welding, and flame imagery will be presented.

9:20 AM, CC5 +

Growth and Characterization of High Quality Undoped and Si-Doped MBE AlN and $\text{Al}_x\text{Ga}_{1-x}\text{N}$ Layers: L. Kirste¹; N. Teofilov²; K. Thonke²; R. Sauer²; J. Ludwig³; K. W. Benz¹; *Dirk G. Ebling*¹; ¹University

of Freiburg, Freiburg Matls. Rsch. Ctr., Stefan-Meier-Str.21, Freiburg D-79104 Germany; ²University of Ulm, Abteilung Halbleiterphysik, Albert-Einstein-Allee 45, Ulm D-89069 Germany; ³University of Freiburg, Faculty of Phys., Hermann-Herder-Str., Freiburg D-79104 Germany

AlN and Al_xGa_{1-x}N layers with high Al contents offer a wide field of applications ranging from optical UV filters and insulating layers to optoelectronic devices like UV detectors due to the large band gap ranging from 3.4 eV to 6.2 eV. In addition, the thermal stability of the materials allows to fabricate high temperature devices. For the applicability of nitride layers a sufficient material quality is necessary, particularly facing crystal quality, impurities and appropriate doping. A basic problem for device fabrication is the high dislocation density of the layers in the range of several 10¹⁰ cm⁻² and the lack of doping of AlN and Al_xGa_{1-x}N layers with high Al contents. To study the influence of the growth parameters on structural properties and crystal quality epitaxial layers of AlN and Al_xGa_{1-x}N were grown on Si-terminated SiC- and sapphire substrates by varying substrate temperature, growth rate, and III/V ratio. The experiments were carried out in a RF-plasma enhanced MBE-system with integrated UHV-STM/AFM. The surface structure was correlated to dislocation densities by comparing the AFM images to TEM cross sections and plane views. The alloy composition of the Al_xGa_{1-x}N layers was studied by RBS-measurements and X-ray diffraction and the results were compared to the optical properties obtained from cathodoluminescence. Remarkable deviations from the ideal composition are observed for Al/Ga-ratios of 1 connected with a variation of the growth rate. This is attributed to a change of growth mechanism at this Al/Ga flux ratio. A clear increase of the optical bowing parameter is observed from CL-measurements for the entire range of alloy composition by reducing the growth rate. For the electrical characterization ohmic contacts were performed on undoped and on Si-doped AlN layers by Ni/Al-contacts. Undoped AlN-layers show high resistivity in the order of several 10⁹ Ωcm at RT. From temperature dependent measurements an activation energy of 0.44 eV is obtained for the conductivity very close to the theoretically expected value for the nitrogen vacancy of 0.5 eV. By Si-doping it was possible to reduce the high resistivity of the AlN layers by 6 orders of magnitude. The obtained Si-concentration was about 10¹⁹ cm⁻³. The remaining resistivity will be discussed according to a compensation model considering deep mid gap levels induced e.g. by oxygen or vacancies.

9:40 AM Break

10:20 AM, CC6

Upconversion Luminescence from FIB Er-Implanted GaN Films: Liang Chium Chao¹; Boon K. Lee¹; C. J. Chi¹; J. Cheng¹; I. Chyr¹; R. Birkhahn¹; Andrew J. Steckl¹; ¹University of Cincinnati, ECECS, 899 Rhodes Hall, P.O. Box 210030, Cincinnati, OH 45221-0030 USA

Rare earth ions have been widely doped into insulators such as fluoride and oxide compounds for laser and optical communication applications. If sufficient light emission can be obtained from rare-earth-doped semiconductors, monolithic optoelectronic devices will be realized which will greatly simplify and reduce the cost of modern optical communication systems. Recently visible and/or infrared emission have been obtained from a variety of erbium-doped WBGs materials, such as SiC, GaAs, InP and GaN. Among them, GaN has drawn the most attention. To date, photoluminescence (PL), electroluminescence (EL) and cathodoluminescence (CL) have been obtained from Pr, Eu, Dy, Er, and Tm-doped GaN. This indicates that GaN is an excellent host for the incorporation of rare earth elements. We report green upconversion luminescence from FIB Er-implanted GaN films after annealing. The maximum upconversion intensity was obtained at a dose of 1~2×10¹⁵ atoms/cm², which corresponds to an atomic percentage of 0.3~0.6%. Using this Er dose, a set of GaN samples were implanted and annealed in a tube furnace at 1100°C in a nitrogen ambient for various time duration. The upconversion spectra were obtained by pumping the GaN:Er samples with a red (at 840 nm) and an IR (at 1 μm) laser. Our results showed that after 100 seconds annealing, emission was observed at 538 nm and 559 nm when the sample was pumped by the 1 μm laser. We have labeled emission at these two wavelengths as corresponding to "site A". After 300 seconds annealing, both site A and new site B (526 nm and 547 nm) were observed when the sample was pumped by 1 μm laser and 840 nm laser, respectively. After one hour of annealing, only site B remained, regardless of which laser was used. The wavelength shift between site A and site B is 12 nm, which

corresponds to an energy difference of ~50 meV. Emission from both sites is due to the 4f transition of Er³⁺ from ²H_{11/2} and ⁴S_{3/2} to the ground state but they must have some difference in crystal field. For site A, the green intensity from ²H_{11/2} to the ground state is stronger than that from ⁴S_{3/2} to the ground state. While in site B, the upconversion intensity from ⁴S_{3/2} is stronger. Similar phenomena were also observed from annealed in-situ MBE grown Er:GaN. A comparison between the FIB implanted sample and MBE in-situ grown sample will be presented. We believe that the transition from site A to site B is due to GaN decomposition under high temperature annealing. Site A to site B transition will also be compared against GaN dissociation rate.

10:40 AM, CC7 +

Nitride Semiconductors for Direct Photoelectrolysis of Water using Solar Energy: Joseph D. Beach¹; Reuben T. Collins¹; John A. Turner²; Oscar Khaselev²; Ashish Bansal²; Joan M. Redwing³; Robert J. Hauenstein⁴; Mark L. O'Steen⁴; ¹Colorado School of Mines, Phys. Dept., Golden, CO 80401-1887 USA; ²National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA; ³ATMI Epitronics, 21002 N. 19th Ave., Ste. 5, Phoenix, AZ 85027 USA; ⁴Oklahoma State University, Phys. Dept., PS-145, Stillwater, OK 74078-3072 USA

Direct photoelectrolysis of water uses an illuminated semiconductor immersed in an aqueous solution to drive the net electrochemical reaction 2 H₂O (l) → 2 H₂(g)+O₂(g). For a semiconductor to be used as an efficient photoelectrode in this process, it must be photoelectrochemically stable, have proper band edge energies relative to the water-splitting half reactions, and have a band gap of approximately 1.8 eV. While oxide semiconductors such as TiO₂ have excellent stability and appropriate band edge energies, their band gap is too large for efficient solar applications. Smaller band gap materials such as GaAs and GaP, on the other hand, lack photoelectrochemical stability and/or proper band edge energy. The III-nitride semiconductors are known for their chemical stability and compositionally dependent band gap, but their suitability for use as a water-splitting photoelectrode has not been adequately explored. In this work, the photoelectrochemical stability and open circuit potential of GaN has been studied in aqueous solutions with varying pH. Results show that both n-type and p-type GaN under illumination have an open circuit potential adequate for splitting water over a wide range of pH. Comparison of Hall measurements made before and after 4000 s of water splitting show that hydrogen evolution at the p-GaN surface does not passivate the material's acceptor dopant (Mg). Testing of samples at 0 V applied bias shows p-GaN to be photoelectrochemically stable in both strong acid and neutral solutions, and n-GaN to be photoelectrochemically stable in strong acid. Based upon these results, further research using lower band gap nitrides such as In_xGa_{1-x}N is being pursued in an effort to achieve more efficient utilization of the solar spectrum.

11:20 AM, CC8 Late News

11:40 AM, CC9 Late News

Session DD. Nanostructure Fabrication - I

Friday AM Room: Driscoll Center North -
June 23, 2000 Pub

Session Chairs: David Janes, Purdue University, West Lafayette, IN 47907-1285 USA; Werner Seifert, University of Lund, Solid State Phys., Lund 221 00 Sweden

8:00 AM, DD1 *Invited

Lithographically-Induced Self-Assembly (LISA) of Nanostructures: Stephen Y. Chou¹; Paru Deshpande¹; Lei Zhuang¹; Lei Chen¹; ¹Princeton University, Nano. Struct. Lab., Dept. of Elect. Eng., Princeton, NJ 08544 USA

Lithographically-induced self-assembly (LISA), discovered recently, offers a new paradigm to pattern micro/nano structures either in a resist or

directly in an active material [1,2]. LISA patterns a material by a delicate interplay between the electrostatic force (between the material and the mask) and the electro-hydrodynamic instability (in the material when it is in a liquid state), without using any radiation, chemical development, and etching. In LISA, a mask is placed a distance above an initially flat film, and the film self-forms, upon being heated to a liquid state, micro/nano patterns. Depending upon the experimental conditions, the patterns created by LISA process can be either arrays of periodic structures (e.g. pillars and rings) with a period much smaller than the dimension of the mask pattern, or duplications of the identical patterns on the mask (The identical duplication is coined lithographically-induced self-construction (LISC) to be distinct from periodic patterns). Furthermore, the location and the lattice structure of each LISA pattern array can be precisely controlled by the boundary of the mask pattern. The physical origins, the patterns, the dynamic behavior of pattern formation, and the applications of LSIA and LISC will be presented.

8:40 AM, DD2

Coulomb Crystals: A New Nanoscale Self Assembly Technique with Rapid Throughput: *Supriyo Bandyopadhyay*¹; Paul Frazer Williams¹; Latika Menon¹; Deyang Yu¹; Yi Liu²; Jayaram Betanabhatla³; ¹University of Nebraska, Dept. of Elect. Eng., Lincoln, NE 68588-0511 USA; ²University of Nebraska, Dept. of Mech. Eng., Lincoln, NE 68588 USA; ³University of Nebraska, Dept. of Phys., Omaha, NE 68131 USA

Coulomb Crystallization is a novel self assembly technique for fabricating ordered two dimensional arrays of nanostructures (quantum dots). It has some potential advantages over more conventional techniques such as Stranski-Krastanow growth of quantum dots or electrochemical self-assembly. Coulomb crystals are much more ordered than Stranski-Krastanow quantum dots, the size selectivity is better, and unlike electrochemical self assembly, this is a “dry” plasma-based technique which is compatible with materials that abhor water. In this technique, size selected nanoparticles of a desired material (produced by processes such as sol-gel and then size selected by sieving through commercially available nanoporous membranes or electrochemically self-assembled nanoporous films) are introduced into an RF plasma, charged negative by the plasma, and then made to levitate above a negatively charged driving electrode. Under appropriate conditions, the “dressed” Coulomb interaction between the particles causes them to self-order into a two dimensional quasi periodic lattice with a “lattice constant” on the order of the Debye screening length in the plasma. One is able to “vary” the lattice constant continuously by varying the plasma density. This flexibility is not easily available in other self-assembly techniques. We have produced Coulomb crystals of a variety of materials in a plasma and, for the first time, successfully transferred them to a substrate. These particles have been directly imaged with TEM, AFM and other microscopy. They have been characterized by capacitance spectroscopy and magnetic measurements. SQUID measurements have shown that Coulomb crystals of the high T_c superconductor YBCO exhibit an increased transition temperature because of quantum confinement which results in a discretization of the quasi particle density of states. To our knowledge, this is the first time that a superconductor has exhibited an increased transition temperature as a result of quantum confinement. It should be noted that most oxide superconductors cannot be handled by traditional nanoscale self assembly techniques, especially aqueous electrochemical self assembly techniques, since oxide superconductors dissociate in water. Coulomb crystallization can also be potentially married with lithography to evolve a comprehensive package for nanosynthesis. This is an important goal since any circuit chip containing self-assembled nanoscale features must be ultimately interfaced with the external world (for data input/output) by lithographically defined contacts. One would define a contact on a wafer by lithography, charge it positive with a capacitively coupled source, and then cause the negatively charged particles in the Coulomb crystal to selectively drop down on the positively charged contacts because of electrostatic attraction. This talk will present preliminary results on self assembled nanostructures produced by Coulomb crystallization. To our knowledge, this is the first time that Coulomb crystallization has been successfully employed as a nanoscale self assembly technique.

9:00 AM, DD3

Nanostructure Fabrication by Charged Clusters: *Nong-Moon Hwang*¹; Mark C. Barnes¹; Doh-Yeon Kim¹; ¹Seoul National University,

Ctr. for Microstruct. Sci. of Matls., Sch. of Matl. Sci. and Eng., Bldg. 37 Rm. 106, Seoul 151-742 Korea

According to a charged cluster model (J. Crystal Growth 162 (1996) 55), charged clusters of nanometer size are suspended in the gas phase in most thin film processes and are a major flux for thin film growth. The existence of these hypothetical clusters was experimentally confirmed in the diamond and silicon CVD processes as well as in gold evaporation. Because of electrostatic and Coulomb interaction arising from charge, the charged gas phase nuclei maintain the uniform and nanometer size. If these clusters are captured on the substrate during a short period of time, individual clusters can make quantum dots structure of highly uniform size and high number density. We produced such quantum dot structures of carbon, silicon, gold and tungsten. The cluster size and distribution were affected by the amount of precipitation, the charge density and the reactor pressure. If these clusters are captured on the substrate during a relatively long period of time, they make a thin film. Small clusters tend to make epitaxial landing, resulting in large grains with well-developed facets. Large clusters tend to make a twin or grain boundary after landing on the growing surface, leading to nano or cauliflower-shaped structure. Charged clusters land preferably on conducting substrates over on insulating substrates, resulting in selective deposition. If the behavior of selective deposition is properly controlled, charged clusters can make highly anisotropic growth, leading to nanowires or nanotubes. In relation to this aspect, silicon nanowires were grown by silicon CVD process.

9:20 AM, DD4 +

Electron Beam Induced Site-Control of Self-Assembled InAs Quantum Dots on InP Surfaces: *Magnus Borgström*¹; Jonas Johansson¹; Lars Samuelson¹; Werner Seifert¹; ¹University of Lund, Solid State Phys., P.O. Box 118, Lund 221 00 Sweden

In recent years quantum dot structures have attracted wide attention because of their importance in physics and device applications based on resonant tunnelling and Coulomb-blockade effects. For this purpose a site-control technique for individual InAs quantum dots (QDs) has been developed using scanning electron microscopy (SEM) carbon deposition and self-organising MOVPE growth. A similar site-control technique has previously been reported [1], using STM induced deposition. It is known that by focusing a SEM electron beam on a single spot, hydrocarbon molecules deriving from residues in the vacuum chamber crack and carbon is deposited on the surface at the position of the spot [2]. Novel devices using these carbon deposits have already been fabricated with this approach [3]. We use such nano-scale deposits on an InP:Sn (001) surface as “nano-masks” on which InP does not grow directly. The deposition rate of the carbon was characterized using a focused electron beam and single pixel exposure in an ordinary lithography system. The deposits were created on a base structure consisting of InP(substrate)/GaInAs/InP(7nm barrier). By overgrowing the partially passivated surface with InP, nano-holes are developed above the carbon deposits. The sample is then etched in oxygen plasma to remove the carbon. Afterwards the sample is overgrown in a second overgrowth step with InAs (0.9 monolayers, self-assembling into dots)/InP/GaInAs. InAs QDs self-organise at the hole sites. With this approach one obtains a structure which is functioning as a vertical transport device with the current restricted to the openings in the InP barrier obtained by InP overgrowth. Conditions were found where in the concave sinks above the openings just one InAs dot nucleates due to migration of In over the more slowly growing facets to the (001) InP bottom plane in the hole. [1] S.Kohmoto, H.Nakamura, T.Ishikawa and K.Asakawa Appl. Phys. Lett 75 (1999) 3488, [2] D.J.Keller and C.Chih-Chung, Surf. Sci 268 (1992) 333, [3] N.Miura, T.Numaguchi, A.Yamada, M.Konagai, J.I.Shirakashi Jpn. J.Appl. Phys. part 2, 36 (1997) L1615.

9:40 AM Break

10:20 AM, DD5 +

Dense Arrays of GaAs/InGaAs Nanostructures by Selective Area Growth Using Block Copolymer Lithography: *Ruijuan Rian Li*¹; Zhijuan Wei²; Paul Daniel Dapkus¹; Mark Edward Thompson³; Christopher K. Harrison⁴; P. M. Chaikin⁴; Richard A. Register⁵; Douglas H. Adamson⁶; ¹University of Southern California, Dept. of Elect. Eng. and Electrophys., Seaver Sci. Ctr., Rm. 510, 920 W. 37th St., Los Angeles, CA 90089 USA; ²University of Southern California, Dept. of Phys., Seaver Sci. Ctr., Rm. 505, 920 W. 37th St., Los Angeles, CA 90089 USA; ³University of Southern California, Dept. of Chem., Los Angeles,

CA 90089 USA; ⁴Princeton University, Dept. of Phys., Jadwin Hall, Princeton, NJ 08544 USA; ⁵Princeton University, Dept. of Chem. Eng., Princeton, NJ 08544 USA; ⁶Princeton University, Princeton Mats. Instit., 70 Prospect Ave., Princeton, NJ 08544 USA

While the Stranski-Krastanow (SK) growth mode has been well used for the self-assembled growth of quantum structures, it is inherently limited to strained material systems. The relatively broad size distribution and the random nucleation of the quantum structures obtained by SK mode are two factors which impede achieving the full potential of these quantum structures in many practical applications. Here we report the fabrication of dense arrays of $\text{In}_x\text{Ga}_{1-x}\text{As}$, with x in the range of 0 to 1.0, by selective area growth in self-assembled nanoscale features patterned by block copolymer lithography. A monolayer of the diblock copolymer PS-PI (polystyrene-polyisoprene) was spin-coated in toluene onto a 15 nm thick SiN_x film on a GaAs wafer surface. Because the polymer chains used in the diblock copolymer are chemically different, PS and PI tend to aggregate into domains when the film is vacuum annealed at $\sim 165^\circ\text{C}$, with PI forming ordered spherical domains embedded in the PS matrix. Ozone bubbled through deionized water is used to remove the PI to form a thin film template with a monolayer of spherical voids embedded in PS owing to the cleavage of carbon-carbon double bonds in the PI chains. CF_4 plasma etching was used to transfer the pattern into the SiN_x mask layer film to expose the GaAs surface underneath. The resultant mask pattern in the SiN_x film is an array of hexagonally ordered holes, with a diameter of ~ 20 nm, a center-to-center spacing of ~ 40 nm and a density of $\sim 10^{11}/\text{cm}^2$. GaAs has been then selectively grown into the hole arrays using metalorganic chemical vapor deposition, forming dense arrays of GaAs nanostructures. These nanostructures were characterized by tapping mode atomic force microscopy to be 23 ± 3 nm in diameter and by field-emission scanning electron microscopy to be 14 ± 1 nm in height. $\text{In}_x\text{Ga}_{1-x}\text{As}$ nanostructures, with x as high as 1.0, can be obtained in the same fashion. However, nanostructures with higher indium composition shown worse size uniformity, which can be improved by the growth of a thicker GaAs buffer layer before the InGaAs layer. We speculate that the migration of indium atoms is very sensitive to the surface steps and the growth of a thicker GaAs buffer somehow helps to provide a smoother surface. In summary, the technique we present here may offer some advantages over the SK growth mode in terms of the fabrication of practical quantum structures for various potential applications.

10:40 AM, DD6

A New Quantum Structure: Nano-Octahedra of MoX_2 , $X=\text{S,Se}$: Philip A. Parilla¹; Anne C. Dillon¹; Kim M. Jones¹; Bruce A. Parkinson²; Michael J. Heben¹; ¹National Renewable Energy Laboratory, Basic Sci. Ctr., MS 3213, 1617 Cole Blvd., Golden, CO 80401 USA; ²Colorado State University, Dept. of Chem., Fort Collins, CO 80523 USA

We report on a new type of quantum nano-structure: small closed octahedra of MoX_2 [1] where $X=\text{S,Se}$. Similarly to graphite, MoX_2 is a highly layered material that can form nested polyhedra and nanotubes. Until now, the analogy with carbon was incomplete since no closed structures akin to the fullerenes with discreet sizes and shapes had been reported. The term "fullerene" applies to small caged carbon structures formed by the seamless integration of graphite fragments. Closure is favored when the energy saved by dangling bond elimination outweighs the energy cost of curvature-induced strain. The smallest cages can only be stable when strain energy is adequately distributed by a highly symmetric structure which also satisfies bonding requirements. This last concept is the defining characteristic of a "true" fullerene, such as C_{60} , and has only now been demonstrated outside of the carbon family. Similar to the carbon fullerenes, closed inorganic cages should be highly symmetric and occur in discreet sizes with jumps in the number of atoms from one size to the next. We have prepared highly symmetric 2- and 3-layer nano-octahedra of MoX_2 in discreet sizes by pulsed laser ablation. These nano-octahedra appear to be minimum energy configurations and therefore may be the first true "inorganic fullerenes". Extensive analysis and modeling of TEM images clearly support a regular octahedral structure as well as a discreet size distribution. We will also discuss preliminary investigations into producing inorganic fullerenes with other transition metal dichalcogenides. [1] "The first true inorganic fullerenes?", P. A. Parilla, A. C. Dillon, K. M. Jones, G. Riker, D. L. Schulz, D. S. Ginley, and M. J. Heben, Nature 1999, 397 (6715).

11:00 AM, DD7

A Simple Purification of Single-Walled Carbon Nanotube Materials: Anne Catherine Dillon¹; Thomas Gennett¹; Jeffrey L. Alleman¹; Philip A. Parilla¹; Kim M. Jones¹; Michael J. Heben¹; ¹National Renewable Energy Laboratory, Basic Sci., NREL, 1617 Cole Blvd., Golden, CO 80401 USA

Carbon single-wall nanotubes (SWNTs) have unique electronic properties as the tubes range from semi-conducting to metallic depending on their structure. However, the SWNTs must be thoroughly purified if they are to be used in a variety of projected applications and basic studies. Here we describe a non-destructive, scalable, 3-step purification process which produces materials with > 98 wt% purity. A dilute nitric acid reflux digests, functionalizes, and redistributes the non-nanotube carbon fractions to form a uniform and reactive coating on the SWNTs. This coating is selectively removed by oxidation in air. Raman and inductively coupled plasma spectroscopies (ICPS), and thermogravimetric analysis (TGA) are used to evaluate the purity of the material at each step of the process, and illustrate that very few tubes are consumed. Such a simple purification technique is not currently available and the use of TGA and ICPS defines a technique by which the components in raw and processed materials may be accurately determined on a weight percent basis. We have also developed a unique process for cutting the SWNTs which enables hydrogen adsorption on the purified tubes at up to 7 wt%. Raman spectroscopy measurements have revealed that the hydrogen adsorption occurs with charge transfer suggesting the potential for hydrogen to act as a nanotube dopant.

11:20 AM, DD8

Well-Aligned Carbon Nanotube Array Membrane Synthesized in Porous Alumina Template by Chemical Vapor Deposition: Hulin Li¹; Cheng-Wei Wang¹; Men-Ke Li¹; Shan-Lin Pan¹; ¹Lanzhou University, Chem. Dept., Lanzhou 730000 PRC

Since Iijima discovered carbon nanotubes (CNTs) in 1991, many researchers have been searching for the ways to prepare CNTs in different pattern with great interest. And there has been many reports on the production and physical properties of carbon nanotubes. Large quantities of CNTs can now be produced by either arc discharge or thermal decomposition of hydrocarbon vapor method. However, CNTs produced by these methods are of random orientation, self-gathering, twisting each other, and even mixed with carbon nanoparticles or amorphous carbon, which restricts their experimental characterization and applications. So great attention has been currently paid to the field of fabrication methods capable of producing uniform, well-aligned and monodispersed CNTs array nanostructures. An effective approach is based on template growth, that is carbon atoms are directly deposited in the openings of a self-organized template by chemical vapor deposition (CVD) technology. In this case the size and shape of CNTs are controlled by the structure of the template, and may vary over a wide range according to the template used. The templates commonly used are in two varieties: porous silicon and porous anodic aluminum oxide (AAO) films. In this paper, we report the fabrication of well-aligned and monodispersed CNTs array membrane within the cylindrical pores of AAO template by chemical vapor deposition (CVD). The method that we used is simple, low cost, well controlled and easily reproduced, and the more important is that the highly-ordered and isolated CNTs array films over large areas could be very useful in a variety of applications including high-density data storage, inert membranes for biomedical use, field emission displays, and infrared imaging detectors. Acetylene and hydrogen were used in the CVD process with Fe-catalyzer at 700 under 250Pa. Scanning electron microscope (SEM) and transmission electron microscopy (TEM) were employed to characterize the resulted highly oriented uniform hollow tubes array which had a diameter of about 250nm, a tube density of $5.3 \times 10^8 \text{ cm}^{-2}$ and a length of about 60 μm . The length and diameter of the tubes depend on the thickness and pore diameter of the template. The growth properties of the CNTs array film can be controlled by structure of the template, the particle size of Fe-catalyzed, temperature in the reactor, flow ratio and deposition time. The highly oriented and uniform CNTs array membrane fabricated by this simple method is very much useful in a variety of application.

11:40 AM, DD9 Late News

Session EE. Non-Destructive Testing and In-Situ Monitoring/Control

Friday AM Room: Centennial Halls
June 23, 2000 Cafeteria

Session Chairs: John Roth, HRL Laboratories, Malibu, CA USA 90265; Kurt Eyink, AFRL/MLPO, Wright Patterson Air Force Base, OH 45433 USA

8:00 AM, EE1

Near-Field Surface Photovoltage: *Yossi Rosenwaks*¹; ¹Tel-aviv University, Phys. Elect. Lab., P.O. Box 39040, Tel-Aviv 69978 Israel

Surface photovoltage (SPV) is a well-established technique for the characterization of semiconductors, which is based on analyzing illumination-induced changes in the semiconductor surface potential. The SPV and other related techniques like surface photovoltage spectroscopy (SPS), has been successfully used to study metal-semiconductor interfaces, surface states, bulk defects, and minority carrier lifetime and diffusion length. To date, all the SPV related techniques have a common significant drawback: they do not have high spatial resolution. With the developments of scanning probe microscopy techniques in recent years, the way is paved to conduct SPV measurements with nanometer lateral resolution. In this talk we describe a novel technique called near-field photovoltage (NFPV) which measures the SPV using near-field optical force sensor. The key feature of the technique is that the excited semiconductor sample is in the optical near-field region of a pulled optical fiber that measures the contact potential difference (CPD) between the fiber and the sample using the Kelvin probe force microscopy (KPFM) method. In such a case the illumination spot size is determined by the diameter of the aperture at the end of the tip and is not limited by diffraction. In addition, the light propagation is evanescent i.e. the intensity of the light falls off exponentially with increase distance from the tip edge (perpendicular to the crystal surface). This in combination with the high spatial resolution of the KPFM makes it possible to obtain depth-sensitive two-dimensional photovoltage images in semiconductors, and other materials. The method is demonstrated by photovoltage measurements conducted on buried p-n junctions of III-V compound semiconductors. When the sample was excited under far-field conditions, a decrease in the PV of the whole structure was observed due to a larger photovoltaic effect (band flattening) in the p-n junction. This is due to the fact that under super-bandgap illumination the band bending of the p-n junction decreases and causes a decrease of the structure work function. On the other hand, when the sample was excited and measured with the near-field optical force sensor, an increase in the PV was observed due to band flattening only in the surface space charge region. Our results demonstrate the large surface sensitivity of the NFPV technique, and opens the way for a variety of ultra-surface sensitive SPV measurements and applications.

8:20 AM, EE2 +

Surface Photovoltage Spectroscopy, Photoreflectance, and Reflectivity Characterization of an InGaAs/GaAs/GaAlAs Vertical-Cavity Surface-Emitting Laser Including Temperature Dependence: *Y. S. Huang*¹; *L. Malikova*¹; *Fred H. Pollak*¹; *H. Shen*¹; *J. Pamulapati*²; *P. Newman*²; ¹Brooklyn College of CUNY, Phys. Dept. and NY State Ctr. for Adv. Tech. in Ultrafast Photo. Mats. and Appl., Brooklyn, NY 11210 USA; ²Army Research Laboratory, Sensors and Elects. Devi. Direct., AMSRL-SE-EM, Adelphi, MD 20783 USA

Vertical-cavity surface-emitting lasers (VCSELs) have a number of advantages in relation to other types of semiconductor lasers including single longitudinal mode operation, low divergence, circularly symmetric beam profile, low threshold current, and ease of integration. To achieve optimum performance several demanding criteria need to be satisfied which pushes growth technologies and characterization methods to their limits. The nondestructive characterization of VCSELs presents a considerable challenge since methods such as photoluminescence (including room temperature) are in general not very useful because of the high

reflectivity of the distributed Bragg reflectors (DBRs). We report comprehensive surface photovoltage spectroscopy (SPS) study of an In_{0.2}Ga_{0.8}As (three 80Å QWs)/GaAs/GaAlAs VCSEL (with 32 front mirror elements) in the range of 15K<T<400K. The VCSEL was grown by MBE with an active QW gain region embedded between two DBRs consisting of a 32.5 period AlAs/Al_{0.1}Ga_{0.9}As n-doped high-reflectivity DBR and a 25.5 period AlAs/Al_{0.1}Ga_{0.9}As p-doped output DBR with digital alloy and digital grading. The active region was centered in Al_{0.4}Ga_{0.6}As spacer layers to form a single wavelength cavity. 70nm Al_{0.98}Ga_{0.02}As layers were placed in the VCSEL structures above and below the active region for selective lateral oxidation to provide optical and electrical confinement. The SPS spectra displayed both the fundamental conduction to a heavy-hole exciton (1C-1H) transition from the QW, the cavity mode feature (E_{cav}), as well as a rich interference pattern from the DBRs. For comparison purposes we also performed temperature dependent photoreflectance (PR), at an incident angle of 65°, and normal incidence reflectivity (NIR_B) from the polished back surface. No E_{cav} dip was observed from the front surface because of the large number of front mirror elements. PR exhibited only the 1C-1H transition while the NIR_B had to be used to evaluate E_{cav}. The room temperature SPS data, including the oscillatory features from the DBRs, has been accounted for on the basis of a calculation of the number of photo-excited carriers (PEC), a quantity related to the SPS signal. Thus SPS yields a considerable amount of information about these important device structures with only one, relatively simple, front surface measurement; this method has considerable potential as a powerful, non-destructive tool to characterize wafer-scale VCSELs.

8:40 AM, EE3

Characterization of GaAlAs/GaAs Heterojunction Bipolar Transistor Structures using Surface Photovoltage Spectroscopy: *Fred H. Pollak*¹; *B. Mishori*¹; *L. Kapitan*²; *T. J. Rogers*²; ¹Brooklyn College of CUNY, Phys. Dept. and NY State Ctr. for Adv. Tech. in Ultrafast Photo. Mats. and Appls., Brooklyn, NY 11210 USA; ²RF Micro Devices, 7625 Thorndike Rd., Greensboro, NC 27409 USA

GaAlAs/GaAs heterojunction bipolar transistors (HBTs) have been extensively studied due to their applications for microwave devices. While photoreflectance and contactless electroreflectance can be used to nondestructively characterize the emitter and collector, they yield no information about the parameters of the heavily p-doped base. However, surface photovoltage spectroscopy (SPS) can be used to estimate the p-doping and evaluate the minority carrier lifetime in the base [B. Mishori et al, Appl. Phys. Lett. 73, 650 (1998)]. In SPS the contact potential difference between the sample and a reference electrode is measured as a function of photon energy in a capacitive manner. The SPS spectra are a function of both the absorption coefficient and minority carrier transport properties in the relevant portions of the sample. We present a SPS characterization of two GaAlAs/GaAs HBTs with both high (150) and low (60) common emitter current-gain amplification factors, β . The two separate HBT wafers were grown by MBE on a V100 MBE system; the latter was during the initial startup of the system after reload and cleaning while the former was typical of a conditioned V100 system using RFMD's procedures. The basic unit of the HBTs consisted of 7000Å of n-GaAs collector ($\approx 7 \times 10^{15} \text{cm}^{-3}$), a 1400Å p-GaAs base ($\approx 1 \times 10^{19} \text{cm}^{-3}$), and an 1800Å graded n-GaAlAs emitter ($\approx 5 \times 10^{17} \text{cm}^{-3}$). The β 's were evaluated on a large area HBT 75x75 μm^2 emitter at 1mA collector current extracted from the Gummel plot. The two samples produced significantly different spectra. The high β sample exhibited peaks at about 1.39eV and 1.42eV, similar to that reported by Mishori et al. The former is due to the band gap narrowing related to the high p-doping in the base while the latter is from the GaAs collector region. The low β had an SPS signal only in the region of the GaAs collector. Taking into account that β is governed by the transport properties of the device, a numerical simulation of the spectra has been applied using the mobility and lifetimes of the minority carriers in both the base and collector regions as parameters. For the high β sample the fitting procedure is described in Mishori et al. The best fit to the low β sample was obtained by reducing the minority carrier lifetimes by (a) two orders of magnitude in the base and (b) one order to magnitude in the collector, in relation to the high β simulation. Thus the lack of a base signal from the low β material is a consequence of the low minority carrier lifetime in this section. We estimate that the minority carrier lifetimes in the base/collector can be evaluated to within 30%.

9:00 AM, EE4 +

Photoreflectance Characterization of an AlInAs/GaInAs (Lattice-Matched to InP) Heterojunction Bipolar Transistor Structure with a Chirped Superlattice: *L. Mouroukh¹; L. Malikova¹; Fred H. Pollak¹; B. Q. Shi²; C. Nguyen²; ¹Brooklyn College of CUNY, Phys. Dept. and NY State Ctr. for Adv. Tech. in Ultrafast Photo. Matls. and Appls., Brooklyn, NJ 11210 USA; ²HRL Laboratories LLC, 3011 Malibu Canyon Rd., Malibu, CA 90265 USA*

AlInAs/GaInAs/InP (001) heterojunction bipolar transistors (HBT) have a number of advantages over other commonly used HBT configurations such as graded emitter GaAlAs/GaAs and GaInP/GaAs. These HBTs have lower turn-on voltage which is desirable for low-power signal processing applications. Because of the high electron mobility and transient velocity overshoot of InGaAs, these HBTs provide superior high frequency performance (higher f_T and f_{max}). Furthermore, the substrate commonality (InP) with 1.3 μm and 1.55 μm photonic devices makes InGaAs HBT attractive for optoelectronic integration. Using photoreflectance (PR) at 300K we have characterized an AlInAs/GaInAs/InP (001) HBT with a chirped superlattice (ChSL) in the emitter region. Franz-Keldysh oscillations (FKOs) were observed from the GaInAs collector and the AlInAs emitter, while ChSL displayed oscillatory features. These FKOs made it possible to evaluate the electric fields in the emitter and collector and hence to deduce the carrier concentrations and band gaps in these sections. The sample used in this study was fabricated by MBE on an InP (001) substrate and consisted of 700 nm n-GaInAs ($1 \times 10^{19} \text{ cm}^{-3}$), 700 nm n-GaInAs ($5 \times 10^{15} \text{ cm}^{-3}$), 50 nm p-GaInAs ($2.6 \times 10^{19} \text{ cm}^{-3}$), 10 nm p-GaInAs ($2 \times 10^{18} \text{ cm}^{-3}$), a nine period ChSL (first 6.6 nm p-doped at $2 \times 10^{18} \text{ cm}^{-3}$ while the final 23.1 nm n-doped at $8 \times 10^{17} \text{ cm}^{-3}$), 105 nm n-AlInAs ($8 \times 10^{17} \text{ cm}^{-3}$), 35 nm n-AlInAs ($1 \times 10^{19} \text{ cm}^{-3}$), and 100 nm n-GaInAs ($1 \times 10^{19} \text{ cm}^{-3}$). The PR modulating source was the 635 nm line of a laser diode internally modulated at 200 Hz. The fields (F) [band gaps (E_g)] from the InGaAs collector and AlInAs emitter were 21 kV/cm [0.729 eV] and 182 kV/cm [1.505 eV], respectively. To extract the relevant carrier concentrations we performed a self-consistent Poisson 's-continuity equation calculation of the collector and emitter fields (including the photo-voltaic effect), resulting in $n=5 \times 10^{15} \text{ cm}^{-3}/4.5 \times 10^{17} \text{ cm}^{-3}$ for the collector/emitter. While the former is in good agreement with the intended growth conditions, the latter is somewhat lower. The FKOs also can be used to evaluate the coherence length, $L_{\text{coh}} = \frac{1}{(E_{\text{last FK0}} - E_g)/qF}$, of the electron-hole pair [F.H. Pollak et al, IEEE J. Selected Topics in Quant. Electron.: Applied Optical Diagnostics of Semiconductors, 1, 1002 (1995)]. For the collector FKOs ($E_{\text{last FK0}} - E_g = 0.171 \text{ eV}$, $F = 21 \text{ kV/cm}$ so that $L_{\text{coh}} = 85 \text{ nm}$). The oscillatory features associated with the ChSL have been account for with a calculation based on the equivalence of the potential profile of the ChSL and a uniformly graded band gap [H. Xu et al, Appl. Phys. Lett. 61, 2193 (1992)].

9:20 AM, EE5

The Optical Constants of n-Doped InGaAs/InP (001) Including Moss-Burstein Shift: Experiment and Modeling: *M. Munoz¹;* ¹Brooklyn College of CUNY, Phys. Dept. and NY State Ctr. for Adv. Tech. in Ultrafast Photo. Matls. and Appls., Brooklyn, NY 11210 USA

The optical constants of InGaAs/InP (including doping effects) are important from both fundamental and applied aspects. For example, for the design of a number of device structures such HBTs and resonant tunneling devices (RTD) it is very useful to have dielectric functions, fundamental band gaps, and the shift of the Fermi energy (E_F) with electron concentration (n), the latter being particularly important for RTDs. A possible saturation of E_F with n in this system (in disagreement with existing theories) has recently been the center of much controversy [A. Tsukernik et al, Proc. 24th ICPS, Jerusalem, 1998, p. 35]. Using spectral ellipsometry in the range of 0.35-5.1 eV we have evaluated the complex optical constants at room temperature of a series of n-In_{0.52}Ga_{0.48}As/InP ($1.3 \times 10^{16} \text{ cm}^{-3} < n < 4.1 \times 10^{19} \text{ cm}^{-3}$) samples fabricated by MOMBE. We have observed the fundamental absorption edge, spin-orbit split E_1 - R_1 , ($E_1 + D_1$)- R_1 doublet [$<111>$ directions of the Brillouin zone (BZ)] and E_2 feature [$<100>$ BZ edge]. The data have been fit using a comprehensive model based on the electronic energy-band structure near critical points plus relevant excitonic and band-to-band Coulomb enhancement (BBCE)/continuum exciton effects [T. Holden et al, Phys. Rev. B56, 4037 (1997)]. The Moss-Burstein (MB) shift of the fundamental absorption edge was evaluated by a Fermi level filling factor plus the exciton and BBCE terms. In the highest n region the MB shift

exhibited non-parabolic effects. By using the BBCE term, we have extracted the binding energy ($R_1 \approx 50 \text{ meV}$) of the 2D exciton associated with the E_1 , ($E_1 + D_1$) critical points, in good agreement with effective mass/theory. Based on a study of thermionic emission and diffusion over a barrier with a built-in charge, Tsukernik et al concluded that E_F saturates at about 130 meV (above the conduction band minimum) for $n \geq 1 \times 10^{19} \text{ cm}^{-3}$. In contrast, we found no such saturation and a shift of 230 meV for the highest n ($4.1 \times 10^{19} \text{ cm}^{-3}$). Our MB displacements are in agreement with a Full Potential Linearized Plane Wave Method calculation, which takes into account non-parabolic effects [G.W. Charache et al, J. Appl. Phys. 86, 452 (1999)].

9:40 AM Break

10:20 AM, EE6

In Situ and Ex Situ Spectroscopic Ellipsometry of Low-Temperature-Grown GaAs: *Donald A. Gajewski¹; Nhan V. Nguyen¹; Jonathan E. Guyer¹; Joseph J. Kopanski¹; Curt A. Richter¹; Joseph G. Pellegrino¹;* ¹NIST, Semiconduct. Elect. Div., 100 Bureau Dr., Stop 8121, Gaithersburg, MD 20899-8121 USA

Low-temperature-grown GaAs (LT-GaAs) is an ideal material for device applications such as insulating buffer layers and sub-picosecond photodetectors, due to its high resistivity and recombination rate. These properties are believed to result from the high excess arsenic antisite concentration [$[\text{As}_{\text{Ga}}]$], which increases with decreasing growth temperature T_g and/or As_2 :Ga beam equivalent pressure ratio R_{BEP} . LT-GaAs refers to the epitaxial growth of GaAs at relatively low substrate temperatures ($< 400^\circ\text{C}$) compared to that typically used for GaAs ($\sim 600^\circ\text{C}$). We have performed in-situ spectroscopic ellipsometry (SE) measurements ((1.6 to 3.0) eV) of the pseudodielectric function $\langle \epsilon \rangle$ of LT-GaAs during molecular beam epitaxy growth and ex-situ SE measurements ((1.5 to 6.0) eV) at room temperature. We have systematically studied the evolution of $\langle \epsilon \rangle$ against T_g ((180 to 300) $^\circ\text{C}$), R_{BEP} (4 to 25), and layer thickness ((100 to 1000) nm). The GaAs (001) substrate temperature was controlled using a commercial diffuse reflectance spectrometer (DRS) supplying active feedback to a commercial temperature controller. The DRS provides superior temperature measurement ($\sim 1^\circ\text{C}$ precision) over conventional pyrometers and non-contacting thermocouples, which are notoriously inaccurate below $\sim 400^\circ\text{C}$. To our knowledge, this is the first such systematic study using SE and DRS. The $\langle \epsilon \rangle$ was extracted by fitting the dynamic in-situ SE data acquired during the growth, using the virtual substrate approximation. The results show that for 100 nm LT-GaAs layers with $T_g \geq 210^\circ\text{C}$, the E_1 interband critical point feature broadens and decreases in amplitude, relative to that of GaAs, monotonically with decreasing T_g and/or increasing R_{BEP} . These trends are consistent with an increasing $[\text{As}_{\text{Ga}}]$, as confirmed using x-ray rocking curve (XRRC) measurements of the LT-GaAs layer strain ($\sim 0.1\%$) and near-infrared absorption measurements of $[\text{As}_{\text{Ga}}]$ ($\sim 10^{20} \text{ cm}^{-3}$). Atomic force microscopy (AFM) measurements and numerical modeling of $\langle \epsilon \rangle$ data show that the observed trends cannot be explained by surface roughness effects. The in-situ SE measurements during the growth also display a clear signature of exceeding the "critical thickness limit" h_{epi} , above which the LT-GaAs growth is polycrystalline for $T_g \geq 210^\circ\text{C}$ and amorphous for $T_g \leq 180^\circ\text{C}$, as revealed by XRRC and AFM measurements. The value of h_{epi} was found to decrease monotonically with decreasing T_g : $h_{\text{epi}} \sim 600 \text{ nm}$ for $T_g = 250^\circ\text{C}$, and $h_{\text{epi}} \sim 20 \text{ nm}$ for $T_g = 180^\circ\text{C}$. Room-temperature ex-situ SE measurements reveal that the E_1 , $E_1 + \Delta_1$, E_0' , and E_2 interband critical points all decrease in amplitude and shift to lower energies with decreasing T_g and/or increasing R_{BEP} . The $\langle \epsilon \rangle$ of polycrystalline LT-GaAs layers is anisotropic between $[110]$ and $[-110]$, and the critical point structure is almost completely washed out. These results illustrate that using in-situ SE and DRS enables unprecedented real-time control over $[\text{As}_{\text{Ga}}]$ and the structural properties of LT-GaAs, which could lead to improved performance and reliability of LT-GaAs-based electrical and optical devices.

10:40 AM, EE7 +

Real-Time Feedback Control of CF₄ Plasma Etching Based on In-Situ Spectroscopic Ellipsometry: *Tyler D. Parent¹; Baris Fidan¹; I. Gary Rosen¹; Anupam Madhukar¹;* ¹University of Southern California, Ctr. for the Intell. Manufact. of Semiconduct. (CIMOS), Depts. of Matls. Sci. and Math., 3651 Watt Way, Los Angeles, CA 90089-0241 USA

We have employed spectroscopic ellipsometry (SE) as an in-situ sensor for real-time feedback control of the silicon nitride etch rate in a $\text{CF}_4/5\% \text{ O}_2$ electron cyclotron resonance (ECR) plasma. Fluorocarbon plas-

mas typically produce an etch rate that evolves with time during the etch. This non-constant etch rate could arise due to plasma induced modification of the chamber walls or some other non-constant factor. The inherent run-to-run and during run variability of fluorocarbon etch processing make such plasmas good test vehicles for real-time process control. Our control objective is to drive the measured real-time etch rate to a user specified target value. We determine the real-time etch rate by means of a linear fit to trailing SE silicon nitride film thickness measurements. We employ the microwave power as the actuator for achieving the control objective. Controllers based on both integral control and adaptive one-step-ahead control have been designed, implemented, and tested. The integral controller for our application takes the form $P[i+1]=P+K(e_i-e[i])$, where $P[i]$ is the microwave power setting during the i -th control interval, K is the discrete time integral control gain, e_i is the user specified etch rate target and $e[i]$ is the etch rate measured by the SE at the end of the i -th control interval. Our second controller, the one-step-ahead adaptive controller, approximates the dependence of the etch rate on microwave power as having the form of a second order polynomial, $e(t)=\alpha_0+\alpha_1P(t)+\alpha_2(P(t))^2+at$. The coefficients of the time derivative of this polynomial relationship (α_1 , α_2 , and a) are identified from the SE data during the etch. Also, at each control step the microwave power correction is determined as $P[i+1]=P[i]+(e_i-\tau a[i])/(\alpha_1[i]+2\alpha_2[i]P[i])$, where τ is the control interval ($\tau=i\tau$). Both the integral and adaptive controllers significantly reduce the run-to-run variability in mean etch rate from $\pm 0.45 \text{ \AA}/\text{sec}$ (uncontrolled) to $\pm 0.05 \text{ \AA}/\text{sec}$ (integral control) and $\pm 0.23 \text{ \AA}/\text{sec}$ (adaptive control) and are able to achieve and maintain a target etch rate by adjusting the microwave power. SE based end-pointing has also been implemented and is shown to reduce the run-to-run variation in etched depth from $\pm 70 \text{ \AA}$ (uncontrolled) to $\pm 3 \text{ \AA}$ (SE based end-pointing). This work is supported by the DARPA/AFOSR Multi-disciplinary University Research Initiative (MURI) program under contract number F49620-95-1-0452.

11:00 AM, EE8 +

Combined BEMA-Beckmann and Kirchoff Approach to Modeling Polysilicon for In Situ Two-Channel Spectroscopic Reflectometry RIE Measurements: *Brooke S. Stutzman*¹; Fred L. Terry²; ¹University of Michigan, Appl. Phys. Dept., Elect. Manufact. Lab., 3300 Plymouth Rd., Ann Arbor, MI 48105-2551 USA; ²University of Michigan, Elect. Eng. and Comp. Sci. Depts., 2408 EECS Bldg., 1301 Beal Ave., Ann Arbor, MI 48109-2122 USA

As the semiconductor industry moves towards larger wafers with increasingly smaller device dimensions, timed etches and depositions are no longer sufficient to maintain a high level of throughput. Thus, sensors, which are both robust to the harsh processing environment and capable of being applied in situ, are necessary to reach the next level of advanced process control. These sensors must not perturb the process and must provide useful information in real-time. To date, optical techniques such as spectroscopic ellipsometry (SE) and spectral reflectometry have been applied in in-line process control and are now emerging in the field of in situ process control. One of the difficulties faced by both of these methods, SE and SR, is that of modeling difficult materials such as polysilicon. The rough surface layer of the polysilicon masks the underlying bulk material properties and, due to this difficulty, an effective optical model has not yet been developed. The traditional treatment of the material is modeling it as a rough surface layer with a complex index of refraction given by the Bruggemann Effective Media Approximation (BEMA) and a bulk polysilicon layer with optical constants, again, given by BEMA theory. An alternative approach involves modeling the non-specular scattering of light from the rough polysilicon surface using Beckmann and Kirchoff's electromagnetic scalar scattering theory. In this paper, we will present a hybrid approach to in situ optical metrology, called two-channel spectroscopic reflectometry (2CSR). 2CSR combines both the principals of SE and SR to allow for high accuracy measurements 6ms. Previously, we have reported 0.22A standard deviations for 2CSR repeated thickness measurements and 0.37A/s standard deviation for 2CSR etch rate measurements of materials with well-known optical models. For a 2CSR measurement of a particular n+polysilicon sample, we found a surface roughness layer of $6\pm 5\text{ \AA}$ and a bulk polysilicon thickness of $5128\pm 3\text{ \AA}$ when using only BEMA theory to model the material. In comparison, when we performed a three angle ex situ scanning SE measurement on the same sample, we found a bulk polysilicon thickness of 5109A and a surface roughness layer of 49A which does not agree well

with the above reported 2CSR measurement. However, when we use both the BEMA and Beckmann-Kirchoff models to fit the 2CSR data, we find a bulk polysilicon thickness of $5111\pm 3\text{ \AA}$ and a surface roughness layer of $41\pm 5\text{ \AA}$ which is in much better agreement with the ex situ SE measurement. Using data from the 2CSR, we will present this approach to modeling the optical properties of polysilicon, which combines both the BEMA and the Beckmann-Kirchoff techniques. We will also show results from in situ 2CSR measurements which indicate that the surface of polysilicon actually becomes less rough as the etch progresses.

11:20 AM, EE9

Characterization of Compound Semiconductor Structures from X-Ray Diffraction Data by the Application of a Genetic Algorithm: *M. Wormington*¹; K. M. Matney¹; D. K. Bowen¹; ¹Bede Scientific, Inc., 14 Inverness Dr. East, Ste. G-104, Englewood, CO 80112 USA

We have developed a method for characterizing compound semiconductor structures from X-ray diffraction data. The method uses a type of genetic algorithm, called Differential Evolution (DE), to fit simulated X-ray rocking-curves from structural models against experimental data. The method is automatic, efficient and reliable. Furthermore, it has the great advantage over traditional fitting methods in that it does not readily converge to incorrect structures, for example those caused by harmonic layer thickness values. We have successfully applied the method to many technologically important compound semiconductor structures. We demonstrate the application of the method to the non-destructive characterization of GaAs-based pseudomorphic high electron mobility transistor (pHEMT) and graded SiGe-based heterostructure bipolar transistor (HBT) structures. For the later structure, the X-ray results are compared with those obtained from secondary-ion mass spectrometry (SIMS).

11:40 AM, EE10 Late News

Session FF. Materials Integration: Wafer Bonding and Alternate Substrates

Friday AM Room: Centennial Halls
June 23, 2000 Main Lounge

Session Chairs: Pete Moran, University of Wisconsin, Chem. Eng. Dept., Madison, WI 53706 USA; Matthew Seaford, Air Force Research Laboratory, Matls. and Manufact. Direct., Wright Patterson Air Force Base, OH 45433-770 USA

8:00 AM, FF1 +

Relaxation of $\text{Si}_{0.82}\text{Ge}_{0.18}$ Films Grown on Ultra-Thin Silicon on Insulator Substrates: *E. M. Rehder*¹; D. E. Savage¹; P. D. Moran¹; M. G. Lagally¹; T. F. Kuech¹; ¹University of Wisconsin-Madison, Matls. Sci. Pgm., 1500 Engineering Dr., Madison, WI 53706 USA

SiGe and silicon on insulator (SOI) substrates are emerging technologies for high-speed electronic devices. In this work we examine the combination of these two technologies. Thick layers of SiGe were grown on ultra-thin, SOI substrates using ultra-high vacuum chemical vapor deposition. Commercial bonded SOI substrates were thinned to 20nm. Experiments were conducted to determine the relaxation and interdiffusion of the SiGe/Si interface. The film composition was fixed at 18% Ge, which avoids surface roughening during growth and the subsequent surface nucleation of dislocations. Films were grown at temperatures from 550 to 670°C on SOI and Si substrates with the film thickness extending to 230nm. Atomic force microscopy found the surface of all the samples to have an RMS roughness less than 0.5 nm over a 20x20µm area. All the samples also had long, narrow depressions with depths ranging from 0.5 to 2nm. These are the very first stages of "cross-hatch", where the passage of a threading dislocation leaves a surface step. The depth variation indicates a dislocation multiplication process such as the Frank-Read

mechanism. X-ray analysis found the growth-induced strain in the Si and SOI to be very similar for pseudomorphic and strain-relaxed samples. These growth temperatures yielded no interdiffusion of the Ge into the SOI. Growth temperatures higher than 670°C led to 3-D growth behavior with rapid defect nucleation and correspondingly high dislocation densities. In order to study higher temperature interdiffusion and relaxation, post growth annealing was performed on the pseudomorphic films. These samples showed significant interdiffusion and relaxation following annealing at 1050°C for 30 minutes. The evolution of the strain relaxation process was studied using X-ray reciprocal space maps.

8:20 AM, FF2 +

SiGe on Insulator Fabricated by Wafer Bonding and Etch-back: *Gianni Taraschi*¹; Thomas A. Langdo¹; Matthew T. Currie¹; Christopher W. Leitz¹; Minjoo L. Lee¹; Jessica S. Lai¹; Kenneth C. Wu¹; Eugene A. Fitzgerald¹; ¹Massachusetts Institute of Technology, Dept. of Matls. Sci. and Eng., 77 Massachusetts Ave., Rm. 13-4150, Cambridge, MA 02139 USA

SiGe on Insulator (SiGeOI) is an improved substrate for MOS devices since it combines both the benefits of a buried insulating layer with those of a relaxed SiGe device layer. For example, a thin strained Si channel MOSFET, fabricated on the SiGe layer, has been shown to have a higher mobility compared to bulk Si, namely a 80% increase in electron mobility and 40% for holes. In this work, we have demonstrated the fabrication of SiGe on oxide using wafer bonding combined with grinding and etch-back to remove excess material from the SiGe wafer. Novel etch-stop properties of the SiGe render the bonding and etch-back process practical for the fabrication of SiGeOI. The process begins with the UHVCVD growth of a SiGe graded layer on a Si substrate, followed by a uniform Si_{0.75}Ge_{0.25} layer. The surface of this material is shown to have high roughness due to the underlying strain fields generated by misfit dislocations at the graded layer interfaces. To eliminate the roughness, chemical-mechanical polishing (CMP) is used to smooth the surface prior to a re-growth step during which a 10 nm strained Si layer (which acts as an etch-stop for subsequent etching) is deposited followed by 150 nm of Si_{0.75}Ge_{0.25}. This substrate is then bonded to an oxidized Si handle wafer and annealed at 800°C in a nitrogen ambient for 2 hours. The resulting bonded pair is found to be void free using infrared imaging, and the fracture surface energy deduced from the Maszara technique is 3.7 J/m², demonstrating that the bonding is indeed strong enough to undergo further processing. Following the bonding step, the backside of the SiGe wafer is ground, and a KOH etch at 80°C is performed. The smaller band-gap of the SiGe results in an etch selectivity of approximately 100:1 between Si and Si_{0.80}Ge_{0.20}, hence most of the original substrate and the graded layer (up to the 20% Ge layer) are removed during this etch process. Finally, the remaining SiGe in the graded region is removed using HF:H₂O₂:CH₃COOH (1:2:3), which stops at the strained Si layer and has an etch selectivity of approximately 300:1. The resulting SiGeOI structure is characterized using transmission electron microscopy and atomic force microscopy. The SiGeOI material has the potential to be the ultimate low power/high performance device platform.

8:40 AM, FF3 +

High-Dose Hydrogen Implantation in GaSb for Ion-Cut Bond and Transfer Applications: *Y. Zheng*²; P. D. Moran¹; S. S. Lau²; T. E. Haynes³; T. Hoehbauer⁴; M. Nastasi⁴; T. F. Kuech¹; ¹University of Wisconsin, Dept. Chem. Eng., 1415 Engineering Dr., Madison, WI 53706 USA; ²University of California-San Diego, Dept. of Elect. Eng., San Diego, CA 92093-0407 USA; ³Oak Ridge National Laboratory, Solid State Div., Oak Ridge, TN 37831 USA; ⁴Los Alamos National Laboratory, Matls. Sci. and Tech. Div., Los Alamos, NM 87545 USA

The blistering and bonding characteristics of ion-implanted GaSb have been investigated for the purpose of transferring an implanted thin layer of GaSb onto a semi-insulating substrate for further growth and/or device processing. Two-inch diameter GaSb wafers, (100)-oriented and n-type, were implanted with (i) H ions at 150 KeV and at room temperature with doses ranging between 5x10¹⁶ and 8x10¹⁶/cm² and (ii) He ions at 150 KeV with a similar dose range, but at -140°C to avoid over-heating during implantation. Blisters readily formed on the surface of H-implanted GaSb upon annealing at temperatures as low as 100°C. The blistering time, i.e., the time for blisters to be observable on the surface, appears to have an activation energy of ~0.3 eV. H-induced blistering appears to be uniform across the entire implanted surface; the blisters expand laterally, coalesce

and forming flakes of exfoliated material upon further annealing. The general features of the blistering process for He-implanted samples are similar to that of the H-implanted samples. The blistering time (rate) is greatly increased (reduced) below 350°C and appears to follow a different mechanism with a much higher apparent activation energy of 4.5 eV. Under these conditions, the blister density is less uniform and the surface blisters burst upon further annealing without obvious coalescence of the blisters. Two conditions must be met for the bond and transfer of these ion-implanted GaSb to suitable substrate or handle wafer, e.g. semi-insulating substrate GaAs, with or without an intermediate layer of glass, which in our case is borosilicate glass of varying boron oxide composition: (1) the implanted GaSb wafer must be securely bonded to the handle wafer below the blistering temperature, and (2) the splitting or exfoliation of the implanted layer must occur before the thermal stress between the two bonded dissimilar wafers becomes sufficiently large to cause debonding. Our preliminary results of bonding GaSb on GaAs suggest that the layer transfer process window is limited to between room temperature and 300°C. In this presentation, the inter-relationship between ion dose, ion species, bonding condition, and wafer surface preparation will be discussed.

9:00 AM, FF4 +

Wafer Fusion of GaAs/GaN Heterostructures: *S. E. Monteith*¹; L. S. McCarthy²; S. K. Mathis¹; H. Marchand¹; U. K. Mishra²; J. S. Speck¹; S. P. DenBaars¹; E. L. Hu²; ¹University of California, Santa Barbara, CA 93106 USA; ²University of California, Matls. and Elect. Eng. Depts., Santa Barbara, CA 93106 USA

High-speed high-power devices could benefit from a heterostructure that combines the high mobility of GaAs with the high breakdown fields achievable in GaN. The large lattice mismatch (26%) between these two materials precludes the growth of such high quality heterostructures by conventional epitaxial methods. Wafer fusion, a technique which bonds two materials in intimate contact under elevated temperature and pressure, has been shown effective in forming heterostructure devices from lattice-mismatched materials (e.g. InP-GaAs, InGaAs-Si). An initial study of the first wafer-fused p-GaAs/n-GaN diode has been carried out; this further study systematically explores the optimum range of fusing conditions for n-GaN fused to p- and n-GaAs. I-V measurements made across the fused interface help to delineate the nature of the interface states, and the relative energy band offsets of the GaAs/GaN system. The study presented describes some of those I-V measurements. Unintentionally doped GaN (nominally n-type) is grown by metal-organic chemical vapor deposition (MOCVD). p-GaAs and n-GaAs are grown by molecular beam epitaxy (MBE). The GaAs samples include a buried sacrificial AlAs layer (~0.15-0.3 μm) to aid in the removal of the GaAs substrate after the fusion step. Each GaN sample is fused to either n-GaAs or p-GaAs under an applied pressure of 2MPa in a hydrogen or nitrogen ambient. Fusion conditions are varied over a range of temperatures (650°C-750°C) and times (1 or 2 hours). The GaAs substrate and the AlAs layer are selectively removed in two consecutive wet chemical etch steps; this reveals a GaAs layer fused to GaN on sapphire. Diode structures are fabricated, contacted, and probed. Current-voltage (I-V) measurements show leaky reverse-biased behavior in the pGaAs-nGaN junctions, and indicate substantial interface states in the nGaAs-nGaN data. Corresponding secondary ion mass spectrometry (SIMS) data are also presented, to correlate electrical behavior with the chemistry and structure of the fused interface.

9:20 AM, FF5

Defects at Bonding Interfaces and Compliant Substrates: *P. Kopperschmidt*¹; St. Senz²; ¹Massachusetts Institute of Technology, DMSE Bldg. 13-4087, 77 Mass. Ave., Cambridge, MA 02139 USA; ²Max-Planck Institute of Microstructure Physics, Weinberg 2, Halle D-06120 Germany

Various materials are integrated by homogeneous and heterogeneous direct waferbonding followed by an appropriate annealing procedure. During the annealing procedure at several 100°C, bonded wafers with different thermal expansion coefficients bend due to thermal induced mechanical stress. For electron transmission microscopic (TEM) study, samples of silicon/sapphire, GaAs/sapphire silicon/GaAs, silicon/silicon, GaAs/GaAs and sapphire/sapphire were prepared by cutting and thinning. Defects, voids and precipitates are revealed at the interfaces by TEM in all samples. Several reasons are discussed concerning the origin of the

defects and precipitates: the intrinsic bulk defects, native oxide and the surface morphology. In bonded thin films, the size of the interface defects occasionally surpasses the thickness of the thin film and pinholes are introduced at the surface. In particular, in twist bonded thin films or 'compliant substrates' with a film thickness of several nm, pinholes may play a potential role in twisted grain growth during epitaxy on these substrates. The substrates are topologically structured with a twist bonded layer, randomly threaded with pinholes. Epitaxial grains are growing on the twisted bonded thin film as well as on the untwisted substrate, simultaneously. Twisted grains are separated from untwisted grains by tilt grain boundaries. On growing epitaxial mismatched layer on the twist bonded thin films, the observing threading dislocations can easily glide through the layer. If the gliding dislocations cannot be annihilate at the grain boundaries, they block each other and the gliding velocity decreases drastically. If the distance between two grain boundaries are lower than the mean free path of the gliding dislocations, only very few threading dislocations are observed in the mismatched deposited layer.

9:40 AM Break

10:20 AM, FF6 +

An Approach for Heterogeneous Integration of High Performance III-V Devices onto Silicon Using Field-Assisted Assembly: Christopher D. Nordquist¹; Peter A. Smith¹; Benjamin R. Martin²; Thomas N. Jackson¹; Theresa S. Mayer¹; ¹The Pennsylvania State University, Elect. Matls. and Process. Rsch. Lab., Dept. of Elect. Eng., University Park, PA 16802 USA; ²The Pennsylvania State University, Elect. Matls. and Process. Rsch. Lab., Dept. of Chem., University Park, PA 16802 USA

Heterogeneous integration of III-V microwave and optoelectronic devices onto silicon substrates is of importance for the development of next generation high-performance microsystems. Predicted performance advantages gained from integrating devices fabricated using dissimilar materials has prompted substantial research efforts in areas such as lattice-mismatched epitaxy and wafer bonding. Recently, alternative integration approaches that utilize self assembly techniques to transfer optimized III-V devices from their host substrates onto patterned silicon substrates have been proposed and demonstrated, including fluidic and electrostatic self assembly. Although these techniques have yielded encouraging results, implementation of fluidic self assembly requires the sidewall profile of the assembled III-V device to be tailored to a corresponding etched feature in the silicon substrate. Moreover, demonstration of electrostatic alignment has been limited to placement of millimeter-scale objects with extremely large (kV range) voltages. In this talk, we will discuss a new field assisted assembly technique that has been used to place and align micron-scale objects with low voltages onto a patterned silicon substrate. In the future, variations of this approach will allow monolithic integration of optimized III-V devices directly onto a silicon substrate that contains CMOS logic circuits. The field assisted self assembly technique was investigated by aligning 3 μm thick Au blocks to apertures defined in a Ti/Au metal layer deposited on an oxidized n⁺-silicon substrate. The dimensions of the Au blocks that were used for this study are 150 x 150 μm², which is similar to discrete epitaxial devices such as transferred substrate microwave power heterojunction bipolar transistors. The Au blocks were fabricated by electroplating on top of a sacrificial photoresist release layer that was removed by soaking the substrate in acetone. Prior to placing the Au blocks in isopropyl alcohol that served as the transport medium during field assisted assembly, they were cleaned in piranha to remove organic contamination and chemically functionalized with a multilayer polyelectrolyte to prevent aggregation. The patterned silicon substrate was treated with an oppositely charged polyelectrolyte to minimize undesired adhesion of the Au blocks to the substrate due to Van derWaals attraction. Field assisted alignment was performed by dispensing a dilute solution of IPA containing the Au blocks onto the silicon substrate biased by applying an ac voltage of 100 V_{rms} at a frequency of 1kHz between the top metal layer and the n⁺ silicon substrate. For this aperture design, a nonuniform field emanates from the apertures with the peak field concentrated at the periphery of the aperture. During the alignment process, the substrate was agitated randomly to prevent the Au blocks from settling on the surface of the substrate. Under these conditions, the Au blocks polarize in the electric field, which results in a dielectrophoretic force that causes them to move towards the regions of highest field strength. Using this technique, we have obtained translational and rotational alignment of better than 20μm and 15°.

Optimized aperture layouts are being designed to improve the alignment precision.

10:40 AM, FF7 +

Strain Relaxation of InGaAs/AlAs/GaAs by Lateral Oxidation: Sheila K. Mathis-Yu¹; A. Maxwell Andrews¹; Prashant Chavarkar²; Umesh K. Mishra²; Evelyn L. Hu²; James S. Speck¹; ¹University of California, Matls. Dept., Santa Barbara, CA 93106 USA; ²University of California, ECE Dept., Santa Barbara, CA 93106 USA

Lateral oxidation of AlAs has been shown to strain-relax InGaAs overlayers grown on GaAs substrates. Prior work shows that the misfit (MD) density is decreased by two orders of magnitude during oxidation. We have proposed that the MDs are reactively removed at the oxide/semiconductor interface by oxidation of the dislocation cores. Threading dislocation (TD) densities have not changed, as observed by etch pit density measurements. However, the mechanism of strain reduction is unknown. The current work focuses on understanding the mechanism of strain relaxation. This is done by determining what oxidation parameters affect the amount of strain relaxation. The goal of this study is to use lateral oxidation to improve upon the normally observed variation of strain with growth thickness, in which strain is proportional to h_c/h , where h_c is the Matthews-Blakeslee critical thickness for dislocation formation at equilibrium. In our approach, InGaAs layers (20-40% indium) that were initially compressively strained were grown five to twenty times thicker than the equilibrium critical thickness on top of 500Å AlAs layers on GaAs substrates using molecular beam epitaxy. Although the layers were thicker than h_c , they were only partially relaxed due to kinetic constraints on relaxation by dislocation formation. The structures were then patterned with 100x100μm mesas, with channels etched deeper than the AlAs layers. Finally, the AlAs layers were oxidized in a horizontal tube furnace in a H₂O/N₂ atmosphere at 450°C. The compressive strain in the InGaAs layers is reduced by 0.5% after lateral oxidation at a temperature of 450°C, for the following six samples: (1) In_{0.2}Ga_{0.8}As (20xh_c, 1.4% misfit), (2) In_{0.3}Ga_{0.7}As (20xh_c, 2.1% misfit), (3) In_{0.4}Ga_{0.6}As (20xh_c, 2.8% misfit), and (4-6) In_{0.3}Ga_{0.7}As (5, 10, and 15xh_c). This demonstrates that the composition and strain state of the layers before oxidation do not affect the amount of strain relaxation during oxidation. However, prior results show that the oxidation temperature strongly affects the amount of strain relaxation in the range 410-450°C. Three possible mechanisms for strain relaxation will be discussed, including (i) threading dislocation motion leading to strain relaxation, (ii) interfacial sliding, and (iii) possible oxidation-related tensile stresses originating at the oxidation front. The total amount of strain relaxation in the InGaAs layer (due to relaxation during growth and during lateral oxidation) represents an improvement over conventional InGaAs growth on GaAs substrates, since lateral oxidation makes it possible to approach the equilibrium strain, $\epsilon_m x h_c/h$, without the generation of TDs and with concurrent reduction in the MD density.

Session GG. Characterization of Quantum Dots

Friday PM Room: Lindsey Auditorium
 June 23, 2000 Location: Sturm Hall

Session Chairs: Mark Miller, University of Virginia, Dept. of Elect. Eng., Charlottesville, VA 22903-2442 USA; Akio Sasaki, Osaka Electro-Communication, Dept. of Elect., Kyoto 606-01 Japan

1:20 PM, GG1

Shape Engineering to Improve the Threshold Temperature Dependence in Quantum Dot Lasers: Oleg B. Shchekin¹; Gyoungwon Park¹; Diana L. Huffaker¹; Dennis G. Deppe¹; ¹The University of Texas at Austin, Depts. of Elect. and Comp. Eng., Microelect. Rsch. Ctr., Austin, TX 78712-1084 USA

InAs and InGaAs quantum dot (QD) active regions are rapidly advancing for the use in GaAs-based lasers that operate at wavelengths $\geq 1.2 \mu\text{m}$. Here we demonstrate the importance of engineering the QD shape to control its electronic spectra, and that this electronic spectra plays a critical role in the QD lasers threshold temperature dependence. Through shape engineering we have increased the energy separations between the ground and excited electron and hole states to achieve an energy separation of 104 meV between ground and excited state radiative transitions. To our knowledge, this energy separation is the widest yet reported for either InAs or InGaAs QDs. In addition, we show that this same energy separation plays an instrumental role in controlling the QD threshold temperature dependence. This leads to a measured T_0 (characteristic temperature) of $\sim 90\text{K}$, which is to our knowledge also the highest T_0 yet reported for low threshold single layer QD lasers. The QDs are grown by molecular beam epitaxy, and are formed from 2.7 monolayers of InAs grown directly on GaAs at a substrate temperature of $\sim 515^\circ\text{C}$. These growth conditions are optimized to yield QDs measured by atomic force microscope to have a diameter of $\sim 250 \text{ \AA}$ and a height of $\sim 60 \text{ \AA}$. For photoluminescence studies the QDs are covered with GaAs, which leads to a ground state emission wavelength at room temperature of $\sim 1.23 \mu\text{m}$. This particular QD shape, along with the high GaAs confinement potential, leads to the room temperature energy separation between the ground and first excited radiative transitions of 104 meV. The InAs QD density is $3.1 \times 10^{10}/\text{cm}^2$. Lasers are fabricated that use a single layer of the optimized InAs QDs. The room temperature threshold current density is 43 A/cm². The threshold current density depends only weakly on temperature below 300K. From 77K to 250K the threshold current density increases from $\sim 20 \text{ A/cm}^2$ to $\sim 30 \text{ A/cm}^2$. Around 300K an estimated characteristic temperature for lasing threshold is $\sim 90\text{K}$. To our knowledge this is the highest T_0 yet reported for a low threshold single layer QD laser. For comparison, larger InGaAs QDs that emit at $1.3 \mu\text{m}$ have lateral size of $\sim 300 \text{ \AA}$, energy separations between the ground and radiative transitions of $\sim 66 \text{ meV}$, and T_0 around room temperature of $\sim 30\text{K}$. These larger QDs have density of $\sim 2.3 \times 10^{10}/\text{cm}^2$. Our modeling shows the major difference in the temperature dependence is due to the energy separations of the radiative transitions. In our talk we will discuss more details of the crystal growth, laser fabrication, and threshold temperature dependence. This work has been supported by the DARPA Univ. of New Mexico OptoCenter, and the ARO MURI on the Optoelectronic Eye.

1:40 PM, GG2 +

Lasing from InAs Quantum Dots Embedded in GaAs Microdisk: L. Zhang¹; P. Michler¹; A. Kiraz¹; A. Imamoglu¹; E. L. Hu¹; ¹University of California, Depts. of Elect. and Comp. Eng., Santa Barbara, CA 93106 USA

The effective coupling of semiconductor quantum dots (QDs) to high quality factor (Q) microresonators opens up the possibility for ultra-low threshold, high gain semiconductor lasers. We report here on optically pumped multi-wavelength lasing from self-assembled InAs quantum dots embedded in GaAs microdisk structures. The microdisks have record-high quality factors ($Q > 17,000$, at the limit of our monochromator resolution), and the emission spectra of a $4.5 \mu\text{m}$ diameter microdisk show lasing in 5 well-separated whispering gallery modes (WGMs) in the wavelength ranging between 920 and 990 nm. The estimated threshold pump densities are between 70-200 W/cm². Our samples were grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The disk structure comprises 4nm GaAs, a 20nm Al_{0.3}Ga_{0.7}As cladding layer, a 200nm GaAs central layer, a second 20nm Al_{0.3}Ga_{0.7}As cladding layer, and a 4nm GaAs cap. The 'active layer' of these structures, grown in the center of the 200 nm GaAs layer, comprised either single layers of QDs. 10^5 to 10^9 cm^{-2} (Q1), a higher density, single-layer structure with dot density of 10^{10} to 10^{11} cm^{-2} (Q2), and finally a structure containing two layers of InAs self-assembled QDs, each with density $\sim 10^{11} \text{ cm}^{-2}$ (Q3). The post layer thickness used was either 0.5 or $1 \mu\text{m}$ of Al_xGa_{1-x}As, x ranging from 0.65 to 0.85, grown on top of an AlAs/GaAs buffer layer. Conventional photolithography was used to define circles with diameters ranging from 1.5 to 6 microns. The delineation of the disk feature was made using a wet, HBr-based etchant. Our earlier attempts to use a reactive ion etch to form the disk produced no whispering gallery modes. This may be related to the damage introduced by the ion-assisted etch process. The pedestal layer is defined by etching in a dilute HF solution. Scanning electron micrographs reveal the top disk layer to have a smooth, non-faceted surface with an almost vertical etched profile. Optical pumping was performed at 6K

using a continuous-wave Ti-sapphire laser operating at 760 nm. The light was focused to an approximately 30 μm diameter spot size on top of the microdisks. We have observed well separated WGM lasing peaks from samples Q2 and Q3 no lasing was observed for sample Q1. Our experiments suggest the threshold density of lasing from QDs is $\sim 10^{11} \text{ cm}^{-2}$ for our samples, with Q values in excess of 12,000. Analysis of our QD densities and the PL linewidths of our samples allows us to estimate that about 100 QDs are coupling to each lasing WGM.

2:00 PM, GG3 +

Time-Resolved Micro-Photoluminescence from Single CdSe Quantum Dots: Takeshi Ota¹; Yasuhiro Murase¹; Kenzo Maehashi¹; Hisao Nakashima¹; Chikara Watatani²; Keiichi Edamatsu²; Tadashi Itoh²; Kenichi Ota³; Kazuo Murase³; ¹Osaka University, The Instit. of Sci. and Indust. Rsch., 8-1 Mihogaoka Ibaraki, Osaka 567-0047 Japan; ²Osaka University, Grad. Sch. of Eng. Sci., 1-1 Machikaneyama Toyonaka, Osaka 560-0043 Japan; ³Osaka University, Dept. of Phys. Fac. of Sci., 1-1 Machikaneyama Toyonaka, Osaka 560-0043 Japan

Single quantum dot spectroscopy in CdSe/ZnSe structures has been performed by time-resolved micro-photoluminescence in order to investigate carrier relaxation mechanism in single quantum dots. Self-organized CdSe quantum dots have been formed on ZnSe(100) substrates using molecular beam epitaxy. Macroscopic photoluminescence spectrum at 2.38 eV shows inhomogeneous broadening (spectralwidth of 60 meV) due to fluctuation in dot size, which covers zero-dimensional discrete energy structures. In order to observe single quantum dots, Al mask with sub-micron size apertures are deposited on sample surface using electron beam lithography and liftoff technique. Through the aperture in Al mask, a number of extremely sharp lines (linewidth of 500 ueV) originated from discrete states in the quantum dots are observed. From temperature dependent micro-photoluminescence measurements using cw Ar ion laser, the degree of linewidth broadening of each line due to lifetime broadening effects has been revealed to depend on energy position of the lines which corresponds to the quantum dot size with different energy level spacing of the quantum dots. In the time-resolved micro-photoluminescence, the excitation was performed through a microscope objective by a frequency-doubled, wavelength-tunable mode-locked Ti:sapphire laser whose wavelength is tuned to excite ZnSe barrier layers. The discrete sharp lines exhibit various decay time. These sharp lines come from discrete states (ground states or excited states) in the quantum dots. The lines corresponding to the excited states have shorter decay times compared with those related to the ground states. The higher energy lines over the discrete states are not resolved clearly and the decay time of them is much shorter than that of the ground states. These unresolved lines would originate from higher states with small energy spacing, which may exist above the discrete levels in the quantum dot. These states would make the carrier relaxation fast from two-dimensional states such as barrier layers to the discrete levels in the quantum dots. From the results of the time-resolved micro-photoluminescence measurements, the decay time of each line may mainly represent radiative recombination time and the contribution of the carrier relaxation time from barrier layers to the quantum dot states would be smaller. For further investigation, resonant time-resolved micro-photoluminescence measurements will be performed.

2:20 PM, GG4

Exciton Magnetic Polarons in a Single Diluted Magnetic Semiconductor Quantum Dot: M. Welsch¹; A. A. Maksimov¹; A. McDonald¹; V. D. Kulakovskii¹; A. Forchel¹; Ch. Becker²; L. W. Molenkamp²; G. Landwehr²; ¹Universität Würzburg Am Hubland, Technische Physik, Würzburg 97074 Germany; ²Universität Würzburg Am Hubland, Experimentelle Physik III, Würzburg 97074 Germany

Due to their delta-like density of states, semiconductor quantum dots are often designated as 'artificial atoms', where the energy states can be occupied with a discrete number of electrons and holes. Thereby, the particle spin is of fundamental importance for the optical transitions both due to the Pauli principle and the fact, that e.g. for the heavy hole exciton, only electrons and holes with antiparallel spin are able to recombine radiatively. Recently, we have shown the impact of particle spin (i) on the radiative recombination of excitons and excitonic molecules and (ii) on the electron hole exchange splitting in nonmagnetic II-VI single quantum dots (SQDs). In this contribution, we will discuss the role of particle spin for optical transitions in diluted magnetic semiconductor (DMS) SQDs. For the first time, we have been able to study the interaction of one single electron-hole pair with its magnetic environment directly by comparing a

semimagnetic Cd_{0.93}Mn_{0.07}Te/Cd_{0.60}Mg_{0.40}Te SQD with its electronically identical, but non-magnetic counterpart Cd_{0.93}Mg_{0.07}Te/Cd_{0.60}Mg_{0.40}Te. The samples have been grown on CdZnTe substrates with molecular beam epitaxy, embedding 3 monolayers of Cd_{0.93}Mn_{0.07}Te and Cd_{0.93}Mg_{0.07}Te, respectively, in Cd_{0.60}Mg_{0.40}Te barriers. In order to select individual dots, small Al apertures have been defined by electron beam lithography and lift-off technique. The SQDs are investigated using temperature dependent photoluminescence (PL) spectroscopy and magnetoluminescence. Most interesting, the linewidth of the low temperature PL signal of the DMS SQD is about 4-meV, i.e. more than one order of magnitude larger than for the nonmagnetic SQD! In addition, the linewidth decreases strongly (almost one order of magnitude) if a magnetic field B is applied in Faraday geometry and becomes comparable to that in nonmagnetic SQDs at B=8T. This is shown to be a direct consequence of the kinetics of EMP formation: As the EMP formation time and the recombination lifetime are on the same order of magnitude, the transient variation of the recombination energy results in an increase of the PL linewidth in the case of time-integrated PL measurements. At high magnetic fields, the well-known destruction of the EMP causes a narrowing of the PL line close to the linewidth observed in nonmagnetic QDs. A semiquantitative description of the Zeeman shift and the temperature dependence of the PL signal allows an estimate the EMP binding energy (10.5 meV), the localization radius (about 3 nm), and the internal exchange magnetic field (3.5 T) in DMS SQDs.

2:40 PM, GG5

Charge Carrier Cooling in InP Quantum Dots: Visible and Infrared Transient Absorption Studies: *Randy J. Ellingson*¹; Olga I. Micic¹; Garry Rumbles¹; Arthur J. Nozik¹; Alexandre A. Mikhailovsky²; Victor I. Klimov²; ¹National Renewable Energy Laboratory, Ctr. for Basic Sci., 1617 Cole Blvd., Golden, CO 80401-3393 USA; ²Los Alamos National Laboratory, Chem. Sci. and Tech. Div., Los Alamos, NM 87545 USA

We report on recent investigations of the intraband energy relaxation of charge carriers in indium phosphide (InP) colloidal quantum dots (QDs) using sub-picosecond visible and infrared transient absorption spectroscopy. Recent work has provided evidence that electron-hole interactions serve as a dominant mechanism for energy relaxation in QDs. Knowledge of the QD absorption cross-section and excitation pulse intensity allows us to control the excitation level in terms of the number of electron-hole pairs per dot; we can thereby study the dependence of electron-hole pair density on relaxation dynamics. The typical size distribution of a colloidal InP (III-V) QD sample is slightly larger than that of the typical colloidal II-VI QD sample (e.g. cadmium selenide). By varying the excitation wavelength, however, we achieve size-selective photoexcitation and can elucidate the particle size dependence of intraband energy relaxation dynamics. Employing hole and electron scavengers such as pyridine and methyl viologen as capping groups, allows us to investigate separately the role of charge carriers in intraband energy relaxation dynamics and provides further a method of studying the dynamics of carrier trapping by surface molecules. We report also, the preliminary, transient spectroscopic studies of the sub-bandgap states in InP QDs that are attributed to the recent observation of photoluminescence up-conversion. These studies are aimed at verifying the mechanism proposed for this unusual phenomenon.

3:00 PM Break

3:40 PM, GG6 +

Photoluminescence of InAs Quantum Dots near a Two-dimensional Electron Gas: *Y. H. Luo*¹; J. Wan¹; J. Yeh²; K. L. Wang¹; ¹University of California- Los Angeles, Device Rsch. Lab. Elect. Eng. Dept., 405 Hilgard Ave., Los Angeles, CA 90034 USA; ²University of California-Los Angeles, Elect. Eng. Dept., 405 Hilgard Ave., Los Angeles, CA 90034 USA

Recent developments in epitaxial techniques have permitted the in situ growth of high-quality defect-free quantum dots. Self-assembled InAs quantum dots have been extensively studied by several experimental techniques. Some works have been done on the transport properties of the InAs dots located near a two-dimensional electron gas (2DEG). It was believed that the wave function of the electrons in the 2DEG overlapped with the potential of the InAs quantum dots. However, until now there has been few report on the optical properties of the InAs dots closed to 2DEG. In this work, InAs dots samples with 2DEG and without 2DEG

grown by solid source MBE system were studied by photoluminescence in detail. From the atomic force microscope (AFM), the size of the InAs dots was shown to be quite uniform. The existence of the 2DEG was confirmed from the mobility measured by Hall measurement. The photoluminescence behavior of the InAs dots was studied. Different emission behaviors between the InAs dots and the InAs dots near a 2DEG were observed. It was found that the emission efficiency of the InAs dots was significantly enhanced by the existence of the nearby 2DEG. It was also found that the thermal activation energy of the InAs dots was changed by the 2DEG. The influence of the distance between the quantum dots and the 2DEG was also studied. It was speculated that the 2DEG at the AlGaAs/GaAs interface worked as an electron reservoir to the InAs dots. A model was proposed to explain the experimental data. It was hoped that in this way the optical properties of the InAs quantum dots could be tailored.

4:00 PM, GG7

Anti-Stokes Photoluminescence in Colloidal Semiconductor Quantum Dots: *Don Selmarten*¹; Ehud Poles¹; Olga Micic¹; Arthur Nozik¹; ¹NREL, Basic Sci., 16253 Denver W. Pkwy., Golden, CO 80401 USA

We report the first observation of PL up-conversion (anti-Stokes PL) in quantum-confined semiconductor colloids; this process features very high efficiency at low excitation light intensity. We offer a model to explain our experimental observations that involves a unique mechanism for Up-Converted PL (UCPL). Colloidal quantum dots (QDs) were synthesized by colloidal chemistry methods. The UCPL is experimentally manifest as a tailing spectrum to the blue of the excitation wavelength; the maximum blue shift is about 300 meV. The UCPL cannot be detected at energies above the maximum energy exhibited in the normal global PL emission. The relative intensity of the UCPL generally follows the intensity distribution of the normal global PL emission across the whole PL spectrum (both band-edge and deep trap emission). The UCPL exhibits a saturable, linear dependence on excitation intensity. We suggest that the observed photon up-conversion involves initial photoexcitation of electrons from a sub-gap state (eg. HOMO levels- possibly associated with a P orbital) into the QD conduction band. In particles that are small enough, the photexcited electron may relax to a sub-gap surface trap site. The photogenerated hole may subsequently be promoted to the valance band by an energy transfer mechanism (we believe phonon absorption is the likely mechanism; the low level excitation density excludes the possibility of non-linear effects, and the linear dependence negates a two-photon absorption event). Once in the final electronic states, the electrons can then undergo radiative recombination with holes in the valance band states. We measured the temperature dependence of the UCPL in a film of InP QDs with an average size of 35 Å and deposited on a quartz substrate. We found that the intensity of the normal PL increased with decreasing temperature, while the intensity of the UCPL decreased with temperature; a characteristic of a process associated with activation energy. The temperature dependence of the process suggests that a two-step, two-photon process is not involved and agrees with a phonon absorption model. In summary, we report highly efficient PL up-conversion in colloidal InP and CdSe QDs at low light intensity. The energy of the up-converted PL spans the range of energies displayed by the normal global PL emission of the QD ensemble; this indicates that sub-gap excitation of the QDs produces radiative recombination from the QD bandgap. The sub-gap states involved in the UCPL are attributed to surface states because the intensity of the UCPL is extremely sensitive to surface treatments, such as exposure to HF. We believe the mechanism for UCPL is a two-step process first involving electron trapping in donor-like surface states followed by hole up-conversion to the valance band from acceptor-like surface states.

4:20 PM, GG8 +

Spontaneous Far Infrared Emission from Self Organized In_{0.4}Ga_{0.6}As/GaAs Quantum Dots: *Sanjay Krishna*¹; Omar Qasaimeh²; Pallab Bhattacharya²; Patrick J. McCann³; Khosrow Namjoo³; ¹University of Michigan, Appl. Phys./Elect. Eng. and Comp. Sci., 1301 Beal Ave., Rm. 2327 EECS Bldg., Ann Arbor, MI 48109 USA; ²University of Michigan, Elect. Eng. and Comp. Sci. Dept., 1301 Beal Ave., EECS Bldg., Ann Arbor, MI 48109 USA; ³University of Oklahoma, Sch. of Elect. and Comp. Eng., 202 W. Boyd St., Rm. 448C, Norman, OK 73019 USA

Far Infrared sources (8-20 μm) are in great demand for optical IR spectroscopy, point-to-point atmospheric communication and optical radars. They are also needed for monitoring of chemical species and

pollutants and for remote control and sensing applications. The only present coherent far infrared source is the quantum cascade laser, a unipolar semiconductor laser based on intersubband transitions in quantum wells. Self-organized quantum dots are expected to display far infrared emission and absorption characteristics as the energy spacing of the bound states in these dots lies in the FIR regime. Quantum dot infrared photodetectors (QDIP) based on intersubband and subband-to-continuum transitions have already been reported by us and other groups. In this paper, we report the spectral characteristics of far infrared spontaneous emission from self-organized $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$ interband quantum dot lasers, at 300K and lower temperatures, due to intersubband transitions. Measurements were made with a multi-dot layer near infrared ($\sim 1 \mu\text{m}$) interband laser using Fourier transform infrared spectroscopy. The far infrared signal, centered at $12 \mu\text{m}$, was enhanced after the interband transition reached threshold. This was consistent with the carrier dynamics of the system and can be explained on the basis of the carrier relaxation times that we measured earlier in these dots. After the interband laser reaches threshold, the ground state of the dots get depopulated at a much faster rate, due to the presence of a large number of interband photons. This creates a non-equilibrium carrier population that is favorable for far infrared emission. The interband laser had to be driven well above threshold at 80K to observe the spontaneous emission. This is probably because the carrier relaxation times decrease with decrease in temperature and a non-equilibrium population between the states is harder to achieve and maintain when the ground state population is depleted at approximately the same rate by interband lasing. To confirm that the emission was not due to blackbody heating of the device, blackbody curves corresponding to facet temperatures (estimated by micro-Raman spectroscopy) were fitted for two values of the heat sink temperature. They were found to exhibit very different response around $12 \mu\text{m}$, where the spontaneous emission was centered. Moreover a similar interband laser containing multi quantum well did not exhibit any FIR response, suggesting that the quantum dots are the source of the observed far infrared emission. Further work is in progress to confine the long wavelength mode using a plasmon enhanced GaAs/AlGaAs waveguide and demonstrate lasing. Work supported by National Science Foundation and Army Research Office.

4:40 PM, GG9

Conductance Spectroscopy on InAs Quantum Dot Ensemble: *Kanji Yoh¹*; Hironobu Kazama¹; ¹Hokkaido University, Rsch. Ctr. for Interface Quantum Elect., N13 W8, Kita-ku, Sapporo, Hokkaido 060 Japan

We report an approach of conductance spectroscopy of electron states confined in InAs dot ensemble in a transistor structure by monitoring the conductance modulation of the d-doped channel formed in adjacent to the InAs dots. Atomic-like shell structure of electrons confined in an average dot is obtained by plotting the current peaks versus external magnetic field. We have investigated single electron charging of InAs dots through d-doped channel current. The d-doped channel transistor structure was formed in adjacent to the InAs dots. The average size of the InAs dots were 25 \AA in height and 170 \AA in diameter. The average areal density of the dots was $2.2 \times 10^{10} \text{ cm}^{-2}$. Both numbers were estimated from AFM measurements. From the gate size of $3 \mu\text{m} \times 10 \mu\text{m}$, average number of dots under the gate is estimated to be approximately 6,600. In the nearly pinch-off conditions, Coulomb blockade oscillation was seen when only a narrow current path remains conductive. Interesting characteristics are observed after the channel is turned on. The charging states of the dots under the gate was shown to be monitored by the current peaks due to threshold voltage shift caused by the spontaneous charging of the dots when the Fermi level crosses the dot confined states. Clear current peaks are observed due to threshold voltage shift at spontaneous charging conditions. Obtained gray scale plot of the current versus magnetic field clearly shows shell structure of electrons confined in an "average" dot with two s-states and four p-states. The threshold voltage shift of $\sim 20 \text{ mV}$ corresponds to charging of each InAs dot by a single electron in average. The lateral extent of the wavefunction is estimated to be $\sim 120 \text{ \AA}$ from the diamagnetic shift using the lever factor of 5 which is consistent with the dot size estimation by AFM. We have also noticed weak current oscillations due to Shubnikov de Haas oscillation which overlaps with the current peak traces caused by the threshold voltage shifts discussed above.

Session HH. Dopant and Other Point Defects in Wide Bandgap Semiconductors

Friday PM Room: Sturm Auditorium
June 23, 2000 Location: Sturm Hall

Session Chairs: Christian M. Wetzel, Meijo University, Nagoya 468-8502 Japan; Tom Myers, West Virginia University, Morgantown, WV 26506 USA

1:20 PM, HH1 +

Inhomogeneous Indium Incorporation in InGaN(0001) Surfaces: *Huajie Chen¹*; R. M. Feenstra¹; J. E. Northrup²; T. Zywiets³; J. Neugebauer³; D. W. Greve⁴; ¹Carnegie Mellon University, Dept. Phys., Pittsburgh, PA 15213 USA; ²Xerox Palo Alto Research Center, 3333 Coyote Hill Rd., Palo Alto, CA 94304 USA; ³Fritz-Haber Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, Berlin D-14195 Germany; ⁴Carnegie Mellon University, Depts. Elect. and Comp. Eng., Pittsburgh, PA 15213 USA

The surface structure and growth kinetics of InGaN(0001) surfaces grown by plasma-assisted molecular beam epitaxy have been studied by scanning tunneling microscopy and first-principles theoretical computations. Indium is found to occupy the top two atomic layers, with a full monolayer of In in the top layer and mixed In and Ga occupation in the second layer. Remarkably, an array of small surface pits is observed to form on the surface. The pits are about 1.0 nm in lateral extent and separated typically by 4.5 nm. We interpret the pit formation mechanism as providing strain relief on the surface, particularly for the second layer which is partially occupied by In. A model of the pit structure has been developed in which the top layer In atoms are missing, and there are N vacancies in the third atomic layer. Theoretically, such a structure is found to be energetically favorable for sufficiently high In occupation in the second layer. Importantly, it is found that the presence of the pits leads to an inhomogeneous indium distribution on the surface, with the second layer indium occupation being greatest in and around the pits. The length scale for this inhomogeneity (4.5 nm) is comparable to the length scale of indium compositional fluctuations seen in other experiments suggesting that the surface pit structure observed here may contribute to those fluctuations. A second major result of our study concerns the kinetics of growth on InGaN(0001) and (000-1) surfaces. We find that the former tend to grow with smooth morphology (i.e. indium acts as a surfactant), whereas the latter generally grow with rough morphology. This difference in the growth kinetics can be understood on the basis of the respective surface structures: the (0001) surface contains about 2 monolayers of metal (In or Ga), whereas the (000-1) surface has only a single monolayer. The excess metal present in the former case may act to prevent any accumulation of nitrogen on the surface which would otherwise limit the surface mobility. Furthermore, the nitrogen itself is found to reside between the two metal layers of the (0001) surface, thus leading to a significant enhancement in its diffusivity compared to that for surface diffusion. This work has been supported by the Office of Naval Research and the National Science Foundation.

1:40 PM, HH2 +

Growth Characterization and Optimization of Mg-doped GaN: *Gon Namkoong¹*; W. Alan Doolittle¹; April S. Brown¹; ¹Georgia Institute of Technology, The Sch. of Elect. and Comp. Eng., 791 Atlantic Dr., Atlanta, GA 30332-0269 USA

GaN grown on substrates such as GaAs, Al₂O₃ or SiC with large lattice mismatches result in an extremely high defect density. However, Mg-doped GaN can be grown on lithium gallate (LGO) which is lattice-matched to GaN within $\sim 0.9\%$. Herein, we show that low temperature growth on LGO can also improve the incorporation of Mg into GaN films allowing for $3.5 \times 10^{20} \text{ cm}^{-3}$ Mg and $2 \times 10^{20} \text{ cm}^{-3}$ at 550 and 615°C thermocouple temperatures. We also describe for the first time dramatically decreased incorporation at high Mg flux, as well as the observation and quantification of concentration dependent diffusion/surface segregation. In this study, we have performed an experiment to map out the Mg saturation points

as a function of growth conditions including substrate temperature, III/V ratio, substrate type and polarity. In order to achieve a broad range of substrate temperatures while maintaining high quality GaN films, lithium gallate(LGO) substrates were used for this study but results will also be compared to sapphire substrates. Using lithium gallate (LGO) we can achieve (0004) x-ray diffraction rocking curves full width at half maximum(FWHM) of 277 arc-sec even for extremely N-rich grown 0.5 μm GaN film. GaN films were grown with alternating undoped and Mg-doped layers with Mg flux variations from 1.6e-11 to 1.6e-8 torr beam equivalent pressure (BEP) in seven steps at 550 and 615°C thermocouple temperatures. SIMS was used to detect the seven Mg doped layers. The resulting SIMS profiles taken at Georgia Tech and verified by Evans East, show a linear increase in Mg concentration with BEP until a BEP of 8.0e-10 torr, beyond which the Mg incorporation reduces by factors of 10 for lower temperature and 2 for the higher temperature. More interestingly, to our knowledge, we are the first to report a decreased Mg incorporation above a critical Mg flux, whereas Orton et al have reported the Mg concentration in GaN films remained constant at high fluxes. Furthermore, we find that the magnitude of the decrease in Mg incorporation increases with decreasing substrate temperature. While step profiles of Mg are nearly ideal at both low and high Mg fluxes, considerable smearing of the profile is observed near the critical flux regime. Also observed for the first time is evidence of concentration dependent Mg diffusivity/surface segregation during the growth. While the trailing edge slopes of step profiles remained unchanged with Mg flux, the leading edge slopes increased by a factor of 3 near the critical flux while at higher flux returned to the same slopes as was observed at a low Mg flux. Mg doped GaN films grown by MBE just below the saturation point show \sim 2-0.5 ohm-cm resistivity and p-type conductivity by Hall measurement and thermal probe measurements.

2:00 PM, HH3

Mg Doping-An Example of Classic Surface Accumulation/Segregation During Doping: *Thomas H. Myers*¹; Aaron J. Ptak¹; ¹West Virginia University, Phys. Dept., P.O. Box 6315, 224 Hodges Hall, Morgantown, WV 26506 USA

Magnesium is currently the most technologically important p-type dopant for GaN. Although its behavior has undergone extensive study in the last several years, the incorporation mechanisms for Mg during growth by molecular beam epitaxy (MBE) remain unclear. Previous studies have presented results that indicate Mg incorporation independent of Mg flux over a wide range and evidence for surface accumulation of Mg. Two competing models have been put forth to explain much of the observed behavior. The first assumes the presence of a surface accumulation layer with dopant incorporation driven by segregation effects. The second model assumes the presence of a finite concentration of sites on the growing surface where the Mg is strongly incorporated. We present the results of a study of Mg incorporation for both N- and Ga-polarity oriented GaN that strongly supports the surface accumulation model. Indeed, many of the doping profiles we obtained strongly resemble classic cases of Sn segregation in GaAs or Sb segregation in Si growth. In addition, we observe a significant difference in Mg incorporation between the two polarities, with Mg incorporating at a rate up to 20 times higher for Ga-polarity surfaces. The phenomenon of polarity inversion linked to Mg on the growing surface was observed, and dramatically illustrates the lower incorporation rate that occurs for the N-polarity surface. An additional result of significance is that the presence of atomic hydrogen significantly alters the incorporation kinetics of Mg, decreasing segregation effects while increasing the actual incorporation rate. This work was supported by ONR Grants N00014-96-1-1008 and N00014-99-C-0161, both monitored by Colin E.C. Wood.

2:20 PM, HH4 +

Magnesium Memory Effects in AlGaIn/GaN HBTs Grown by Metalorganic Chemical Vapor Deposition: *Damien J.H. Lambert*¹; Bryan S. Shelton¹; Michael M. Wong¹; Uttiya Chowdhury¹; Ho Ki Kwon¹; Ting Gang Zhu¹; Jian Jang Huang²; Milton Feng²; Russell D. Dupuis¹; ¹The University of Texas at Austin, Microelect. Rsch. Ctr., PRC/MER-R9900, Austin, TX 78712 USA; ²University of Illinois at Urbana-Champaign, Microelect. Lab., 208 N. Wright St., Urbana, IL 61801 USA

We report the growth, processing and characterization of high-quality AlGaIn/GaN heterojunction bipolar transistors (HBTs) by low-pressure metalorganic chemical vapor deposition (MOCVD) with adduct-purified

trimethylgallium (TMGa), trimethylaluminum (TMAI), bis(cyclopentadienyl)magnesium (Cp_2Mg), silane (SiH_4), and ammonia (NH_3) precursors. The epitaxial structures are grown in an EMCORE D125 UTM reactor at pressures \sim 100 Torr. We have varied the growth conditions (e.g., single-step growth, regrowth of the emitter, selective regrowth of the emitter and the base, insertion of a spacer, base thickness) and have studied the correlation of the symmetric and asymmetric X-ray diffraction linewidths, surface morphology, secondary ion mass spectroscopy (SIMS), and emitter, or base doping concentrations upon the amplification coefficient β , the base-emitter and base-collector breakdown, and the emitter-collector leakage of the HBTs. Some device structures were made in a single-step growth process while others were made in a two-step regrowth sequence in order to reduce the Mg memory effect that counter-dopes the emitter layer of the HBTs. We believe that the diffusion of Mg from the base to the emitter contributes to the increase of the series resistance in the devices and is responsible for the degradation of β . A selective regrowth method has been employed to eliminate the non-selective etch process of the emitter to contact the thin base that is difficult to control. With SIMS analysis, we find that Mg diffuses largely into the emitter and slightly into the collector, which artificially increases the base thickness and reduces significantly the gain of the HBTs. Specifically, inserting a short GaN:ud layer on the top of the base, and interrupting the growth after the base, generates a much sharper doping profile of the device. This undoped spacer presumably incorporates diffusing Mg atoms, and becomes part of the p-type base, thus preventing (or reducing) any Mg contamination of the emitter. Preliminary device data from these HBT wafers show a gain dependence upon the base thickness. We have also studied the effect of the RMS roughness of the buried base layer and the asymmetric (102) X-ray rocking curve FWHM values on the Mg diffusion in the emitter. From these studies of surface atomic force microscopy (AFM) measurements on 5x5 μm areas, we have found that the reduction of the RMS roughness down to \sim 0.26 nm, and the dislocation density down to \sim 2-3x10⁸ cm⁻³ for the n-type GaN:Si "thick collector-subcollector layers" grown on sapphire has greatly improved the performance of our HBTs. By optimizing the growth conditions, we have achieved Al_xGa_{1-x}N(x=0.15)/GaN heterojunction bipolar transistors on (0001) sapphire with current gain in excess of β =24 at 300K for the thinnest studied base which was 150 nm thick.

2:40 PM, HH5 +

Investigation of P-Type GaN Co-Doped with Oxygen: *Roman Y. Korotkov*¹; Bruce W. Wessels¹; ¹Northwestern University, Matls. Sci. and Eng. Depts., 2225 N. Campus Dr., Evanston, IL 60208 USA

P-type GaN grown by metal-organic vapor phase epitaxy is usually highly compensated. The nature of the compensating defect is a subject of considerable controversy. Both native defects and impurities, such as Si and oxygen have been indicated as a compensating centers. In the present study p-type Mg-doped GaN has been co-doped with oxygen to determine its effect on the electronic and optical properties. The addition of oxygen had a strong effect on the photoluminescence properties of heavily Mg-doped layers. The blue band at 2.8 eV typically observed in these layers was red-shifted as much as 0.4 eV to 2.4 eV. The amount of shift was dependent on oxygen doping density. With increase in excitation power the band blue-shifted by 0.1-0.2 eV. The observed changes in photoluminescence spectra were attributed to potential fluctuations in the heavily compensated material. Electrical properties of the Mg-doped GaN co-doped with oxygen were investigated. For high oxygen concentration epitaxial layers became n-type consistent with oxygen behaving as a donor.

3:00 PM Break

3:40 PM, HH6

Co-Implantation Studies in GaN: *Brian J. Skromme*¹; Greg L. Martinez¹; Agajan Suvkhanov²; Leonid Krasnobaev²; David B. Poker³; ¹Arizona State University, Dept. of Elect. Eng., P.O. Box 875706, Tempe, AZ 85287-5706 USA; ²Implant Sciences Corporation, 107 Audobon Rd. #5, Wakefield, MA 01880-1246 USA; ³Oak Ridge National Laboratory, Bldg. 3003 MS-6048, P.O. Box 2008, Oak Ridge, TN 37831-2008 USA

Ion implantation is a potentially useful technique for selective n- and p-type doping of GaN. It is also a very useful method to study the behavior of various dopants in this material, as a wide range of species can be controllably introduced into any starting material. The p-type doping of GaN by implantation has been particularly problematic, how-

ever, and has frequently required co-implantation of species such as P to achieve electrical activation. The present work studies the activation of implanted acceptor species in GaN, using low temperature photoluminescence (PL) as a primary tool to study the activation and assess the nature of the various levels introduced. Low dose implantations from 1×10^{15} to 1×10^{17} cm⁻³ were used into high purity starting material grown by hydride vapor phase epitaxy or metalorganic chemical vapor deposition in order to obtain highly resolved optical spectra. The implanted acceptors included Mg, C, and Be, with energies and doses adjusted to yield the same flat depth profile for each species. Co-implantations of Ne, Al, P, and Ar ions at doses of 10^{17} cm⁻³ (or in a few cases, 10^{19} cm⁻³) with the same depth profile were used to create additional damage and/or alter the stoichiometry of the implanted region for each acceptor species. Rapid thermal annealing is performed for 10 s at 1300°C in flowing N₂, using reactively sputtered AlON as a capping material. The Mg implants demonstrate clear optical activation even without co-implantation, showing a strong, sharp (e.g., 2.6 meV FWHM) neutral acceptor-bound exciton (A⁰,X) peak at 3.4704 eV with a localization energy of 12.2 meV, in addition to the pre-existing neutral donor-bound exciton peak at 3.4760 eV. Donor-to-acceptor (D⁰-A⁰) and band-to-acceptor peaks are also observed at 3.270 eV (1.7K) and 3.284 eV (50K), respectively, implying a Mg acceptor binding energy of 224 meV. A new green band also appears at 2.35 eV. With co-implantation, the Mg acceptor-related features become stronger related to the residual donor-related features. For example, the Ar co-implant produces a 4-5X increase in the strength of the (D⁰-A⁰) peaks relative to the residual (D⁰,X) peak. The P co-implants produce a new peak at 3.248 eV, in addition to the usual (D⁰-A⁰) peak around 3.270 eV; the new peak may be related to the isoelectronic nature of P, but further study is underway. The C and Be implanted samples show very poor optical activation without co-implantation, at least 50X worse than that of Mg. No (A⁰,X) peak is observed and only very weak (D⁰-A⁰) peaks appear around 3.385 eV in both cases, although an enhanced yellow (2.2 eV) PL band is observed. The effects of co-implanted species on the optical activation of these species will be described.

4:00 PM, HH7 +

Optically and Thermally Detected Deep Levels in n-GaN: Effect of Hydrogenation: *Adrian Hierro*¹; Daewon Kwon¹; Steven A. Ringel¹; Monica Hansen²; James S. Speck²; Umesh K. Mishra²; Steven P. DenBaars²; ¹The Ohio State University, Elect. Eng. Dept., 205 Dreesse Lab., 2015 Neil Ave., Columbus, OH 43210 USA; ²University of California, Matls. and Elect. and Comp. Eng. Depts., Bldg. 446, Santa Barbara, CA 93106 USA

Deep levels in n-GaN have become prime suspects in limiting the behavior of GaN-based FET's, among other devices. In this paper the properties of deep levels present in unintentionally doped MOCVD-grown n-GaN with and without intentional H incorporation are investigated. Both deep level optical spectroscopy (DLOS) and deep level transient spectroscopy (DLTS) are used to probe the entire n-GaN bandgap. Secondary ion mass spectroscopy (SIMS) was also performed to help identify possible physical sources for the defects. Deep levels at E_c-E_v=0.58-0.62, 1.35, 2.57-2.64 and 3.22 eV are observed in n-GaN for both Schottky and p⁺-n diode configurations, with concentrations in the $\sim 10^{14}$ - 10^{16} cm⁻³ range. Depth resolved DLTS shows that the concentration of the 0.58-0.62 eV level tracks the residual Mg profile found in the n-side of the p⁺-n junction. Comparison of the samples indicates that the 1.35 eV trap concentration possibly correlates with the C concentration. The 2.57-2.64 eV level is detected as a minority carrier hole trap in n-GaN by both DLOS and DLTS. For the first time the thermal and optical cross sections of this trap have been fully determined, providing a complete signature for the 2.57-2.64 eV level. This level is most likely related to the yellow band and shows a similar energy to reported calculations of deep levels produced by V_{Ga}-O and V_{Ga}-donor complexes. Finally, the detected 3.22 eV level is most likely related to either C or Mg residual acceptors in MOCVD-grown n-GaN. The physical origin of some of these levels will be further clarified by comparison to n-GaN grown on a Mg-free MOCVD reactor and by MBE. The n-Schottky GaN sample was RF-plasma hydrogenated in order to observe how hydrogen may alter the properties of each deep level. Only the E_c-E_v=0.62 and 1.35 eV levels are affected as a result of the hydrogenation. The concentration of the 0.62 and 1.35 eV levels decreased by a factor of ≥ 30 and ~ 14 , respectively. It is known that hydrogenation of GaN leads to the generation of C-H and Mg-H complexes, which has a strong effect on the concentra-

tion of active acceptors. Our results indicate for the first time that hydrogenation of n-GaN also helps passivate some of the defects responsible for deep levels found within the bandgap, which may be related to residual C and Mg. The 2.64 eV trap concentration was not affected by hydrogenation, suggesting that the defect responsible for the yellow band is not modified as a result of hydrogen incorporation. The details of the processes involved in the passivation of the defects responsible for the deep levels will be addressed.

4:20 PM, HH8

Electron Beam Induced Increase of Electron Diffusion Length in p-type GaN and AlGaIn/GaN Superlattices: *Leonid Chernyak*¹; Andrei Osinsky²; ¹University of Central Florida, Dept. of Phys., 4000 Central Florida Blvd., MAP 310, Orlando, FL 32816-2385 USA; ²NZ Applied Technologies, 14A Gill St., Woburn, MA 01801 USA

Minority carrier diffusion length is a critical parameter for GaN-based heterojunction bipolar transistors and UV photodiodes. Electron beam of Scanning Electron Microscope (SEM) was used to locally change an electron diffusion length in p-type GaN epitaxial layers and Al_xGa_{1-x}N/GaN (X=0.1, 0.2) superlattice structures grown by MOCVD and MBE techniques. Minority carrier diffusion length measurements by using Electron Beam Induced Current (EBIC), carried out in-situ in the SEM, allowed near-simultaneous monitoring of GaN electrical properties as a function of electron beam irradiation time. A planar metal-semiconductor (Schottky) configuration was used for this purpose. The minority carrier diffusion length, L, was derived from the line-scan EBIC measurements while the electron beam was moved away from the edge of the Schottky barrier. The same line-scan was used for an electron beam irradiation. The diffusion length of electrons in Mg-doped MOCVD-grown p-GaN was found to increase linearly from 0.55 to 2.0 micron with increasing electron beam irradiation time, t, up to 1500 sec. The similar trends, with L increasing from 0.27 to 1.48 micron and from 0.26 to 2.5 micron, were observed for Mg-doped MBE-grown p-GaN and Al_xGa_{1-x}N/GaN superlattices respectively, for the durations of electron beam irradiation comparable to that for the MOCVD p-GaN sample. While the electron diffusion length in p-type (Al)GaIn and GaN structures varies with t, the diffusion length of holes in MOCVD n-GaN material remains unchanged, with L \sim 0.35 micron, for at least one hour of electron beam irradiation. We ascribe the observed increase in minority carrier diffusion length in p-(Al)GaIn to an increase of electron lifetime due to an electron beam-induced charging of deep metastable centers. These centers, located 1.1, 1.4 and 2.04 eV above the valence band edge in p-GaN, are possibly related to Mg doping and are the reason for the persistent photoconductivity in this material. Minority hole diffusion length independence of electron beam irradiation in n-GaN is an additional argument in favor of Mg-acceptor relation to an increase of minority electron diffusion length in p-(Al)GaIn samples. We ruled out a possible involvement of an electron beam-induced Hydrogen debonding from Magnesium, since the above-referenced increase in L was also observed in MBE-grown material, for which no Hydrogen is present in the growth environment. Carrier mobility independence on electron beam irradiation time in p-GaN excludes the role of mobility in minority carrier diffusion length increase.

4:40 PM, HH9

Cross Sectional Scanning Probe Studies of Hydride Vapor Phase Epitaxy GaN Films: *Julia W.P. Hsu*¹; David V. Lang¹; Shulin Gu²; Thomas F. Kuech²; ¹Lucent Technologies, 700 Mountain Ave., Rm. 1D-368, Murray Hill, NJ 07974 USA; ²University of Wisconsin, Chem. Eng. Dept., 1415 Engineering Dr., Madison, WI 53706 USA

It is well established that the quality of GaN film grown on sapphire substrates improves as the film grows thicker. This includes lower dislocation density, higher mobility, and sharper X-ray linewidth. In addition, the free carrier concentration in nominally undoped films is lower in thicker films. Since TEM images reveal a highly faulted layer near the sapphire substrate, this led to the proposal of a highly conducting layer of low mobility near the substrate interface while the bulk film contains lower free carriers. Hence, it would be useful to examine the electrical properties of GaN films in cross sections. We have made cross sectional samples of GaN films grown by hydride vapor phase epitaxy (HVPE) method and study them using electrostatic force microscopy (EFM) and scanning capacitance microscopy (SCM). The cross sectional samples were made using common preparation procedures for TEM samples. The

film thickness varies from 6 to 60 microns. Some samples have a ZnO buffer layer on the sapphire substrates. The ZnO layers were deposited by RF sputtering to a thickness of about 20 nm. The ZnO is not present in the final structure. We find that the GaN materials near the sapphire interface are less resistant to polishing. A small crack of non-uniform width can be seen in topographic images. This is caused by removal of small grains in the interfacial layer. EFM images tell us how surface contact potential (SCP) varies from position to position. SCP is quite uniform across the bulk of film, but shows variations near the substrates in some samples. SCM images show that the bulk of the film is n-type, but there are non-trivial carrier concentration variations. Some defects with electrical signals are also seen. Our results do not support a highly conducting layer near substrate interface. We will examine how the observed electrical property variations depend on film growth conditions and film quality, e.g. X-ray linewidth. The effect of sample preparation procedure will also be discussed.

5:00 PM, HH10

Real Time Observations of the Formation of Nanopipes in GaN: Eric A. Stach¹; Christian F. Kisielowski¹; William S. Wong²; Timothy Sands²; Nathan W. Cheung³; ¹Lawrence Berkeley National Laboratory, Natl. Ctr. for Electron Micro., MS 72-150, 1 Cyclotron Rd., Berkeley, CA 94720 USA; ²University of California, Berkeley, Dept. of Matls. Sci. and Min. Eng., 559 Evans Hall, Mailcode 1760, Berkeley, CA 94720-1760 USA; ³University of California, Berkeley, Dept. of Elect. Eng. and Comp. Sci., 518 Cory Hall, Mailcode 1170, Berkeley, CA 94720-1170 USA

GaN and related alloys have achieved remarkable successes in the areas of short wavelength optoelectronics and high power devices. This is in spite of the relatively high densities of crystal defects present in these materials. In this work, we present real time in-situ transmission electron microscopy observations that explain the formation process of a particular type of crystalline defect-the so-called "nanopipe" or empty core dislocation. In order to produce samples suitable for in-situ TEM observation, we selectively removed the GaN layers from the sapphire (0001) growth substrate using a laser lift off technique. The resulting stress-free, free-standing layers of GaN were then ion-thinned to electron transparency and annealed to temperatures in excess of 1000°C within the objective lens of the electron microscope. We find that upon reaching a temperature of approximately 925°C-the temperature at which nitrogen desorption from the material becomes significant-nanopipes form selectively along the cores of those pre-existing dislocations which are pure screw in character. The size of the nanopipes increases with increasing time and temperature as nitrogen desorption proceeds. When dislocations have a mixed screw and edge character, the desorption of nitrogen along the core results in motion of the dislocation along {1-100} directions within the basal plane and the formation of a hollow tube in its wake. This motion does not proceed indefinitely, however, but appears to be limited by the length of tube over which the desorbed nitrogen must travel to escape to atmosphere. No effect of nitrogen desorption on dislocations with pure edge character is seen for temperatures as high as 1050°C. These results have a direct impact on our understanding of the growth of GaN and related alloys, as the crystal growth process by metallorganic chemical vapor deposition and hydride vapor phase epitaxy occur at temperatures where nitrogen desorption is possible. This indicates that the formation of nanopipes during heteroepitaxial growth is, in some fashion, unavoidable. Additionally, it is believed that this mechanism-thermally induced desorption of the light element causing nanopipe formation-is likely to be operative in other wide band gap semiconductors such as SiC, InGaN and AlGaIn.

Session II. Nanostructure Fabrication - II

Friday PM Room: Driscoll Center
June 23, 2000 North - Pub

Session Chairs: Supriyo Bandyopadhyay, University of Nebraska, Dept. of Elect. Eng., Lincoln, NE 68588 USA;
Evelyn Hu, University of California-Santa Barbara, ECE Dept., Santa Barbara, CA 93106 USA

1:20 PM, III +

Semiconductor Nanostructure Formation Using Dip-Pen Nanolithography: A. J. Blatner¹; D. A. Weinberger²; S. Hong²; T. B. Higgins³; B. W. Wessels¹; C. A. Mirkin²; ¹Northwestern University, Depts. of Matls. Sci. and Eng., Matls. Rsch. Ctr., Evanston, IL 60208 USA; ²Northwestern University, Dept. of Chem., Matls. Rsch. Ctr., Evanston, IL 60208 USA; ³Harold Washington College, Dept. of Phys. Sci., Chicago, IL 60601 USA

We have successfully fabricated relief nanostructures in silicon through a simple technique of dip-pen nanolithography and wet chemical etching. In this process, a self-assembled monolayer (SAM) is patterned on a gold-coated substrate using an atomic force microscope (AFM). The AFM tip is coated with a supersaturated solution of an alkanethiol. As the AFM tip is brought near the sample, the alkanethiol molecules are transported through a water meniscus to the gold surface. The alkanethiol molecules then self-assemble into a cohesive monolayer. The SAM then acts as a mask. This enables the removal of the exposed gold, while leaving a layer of gold at precise locations on the sample. With the gold removed, the underlying substrate is accessible for etching and nanostructure formation. Using this technique, it is possible to write the alkanethiol on a clean gold surface with a <30 nm linewidth. Upon subsequent etching of the gold, we have been able to fabricate pillars <100 nm in diameter in Si (001). We are also applying this technique to the fabrication of GaAs nanostructures.

1:40 PM, II2 +

Self Alignment of Patterned Substrates using Hydrophobic/Hydrophilic Interactions: Donna C. Furnanage¹; Benjamin R. Martin²; Daniel L. Dermody²; Thomas N. Jackson³; Theresa S. Mayer³; ¹The Pennsylvania State University, Dept. of Elect. Eng., 121 Electrical Engineering East, University Park, PA 16802 USA; ²The Pennsylvania State University, Dept. of Chem., 152 Davey Lab., University Park, PA 16802 USA; ³The Pennsylvania State University, Dept. of Elect. Eng., 216 Electrical Engineering West, University Park, PA 16802 USA

Self alignment of structures with micron or better precision has applications in the area of heterogeneous materials integration, which includes III-V optoelectronic device and silicon integration and microelectromechanical component assembly. The use of hydrophobic-hydrophilic derivatization of surfaces has been studied previously by Whitesides et. al. [1] for self assembly of millimeter sized polymeric and metallic components. This group demonstrated that macroscopic alignment can be achieved by minimizing the surface energy between the hydrophobic and hydrophilic surfaces of these components. We have extended this approach to demonstrate that hydrophobic-hydrophilic interactions can be used to achieve micron-scale alignment of features patterned on large area planar surfaces. Variations of this passive, self-alignment process could be used when human and/or machine handling is too costly or not sufficiently precise. Alignment using hydrophobic-hydrophilic interactions was studied by defining gold patterns consisting of a 5'6mm border that enclosed smaller, 4-10mm features onto silica substrates. Each pattern also included features that used to measure the alignment precision. In order to study the border area-to-perimeter ratio dependence on the alignment precision, four pairs of samples with border widths ranging from 80-2000mm were fabricated. Each pair contained a 2.5cm and 5cm diameter substrate, which were patterned with mirror images. The gold patterns on each of the samples were rendered hydro-

phobic using an octadecanethiol self-assembling monolayer, while the silica substrate remained hydrophilic. After monolayer assembly, pairs of silica substrates were covered with water and brought into contact. Agitation of the wafer pairs allowed the smaller top substrate to move across the bottom substrate until the gold patterns on the two substrates aligned. In each case, a much larger force was required to misalign the pattern on the substrates, indicating that the alignment is robust. In this study, an alignment precision of better than 1 nm was obtained on the substrate that had the smallest border width of 80nm. Increasing the width of the border while keeping the outer perimeter constant degraded alignment precision, with the largest border width resulting in the worst alignment. This suggests that the driving force for the self alignment is the interaction of the hydrophobic-hydrophilic interface, which places an upper limit on the border area-to-perimeter ratio of the hydrophobic regions that can be aligned with micron-scale precision. The results of these experiments demonstrate that passive alignment can be used to position surfaces with micron-scale precision. Although this first demonstration used flat surfaces, the alignment technique is general and could also be used to align components with curved or other complex geometries. I. N. Bowden, I. S. Choi, B. A. Grzybowski, G. M. Whitesides, *J. Am. Chem. Soc.*, 121, 5373 (1999).

2:00 PM, II3

AFM Nanolithography for Selective Growth of High-Density Array of ZnCdS/ZnMgCdS Quantum Dots: *Adrian Avramescu*¹; Akio Ueta¹; Katsuhiko Uesugi¹; Ikuo Suemune¹; ¹Hokkaido University, Rsch. Instit. for Elect. Sci., Kita-ku Kita 12 Nishi 6, Sapporo 060-0812 Japan

In recent years, several methods have been proposed for the fabrication of ordered arrays of semiconductor nanostructures such as stress induced self-assembling of quantum dots on vicinal patterned surfaces [1]. These methods offer the capability to prepare highly ordered array of quantum dots, but the density was limited to $\sim 1 \times 10^{10} \text{cm}^{-2}$. In this paper, selective area growth (SAG) of highly ordered array of quantum dots with the high density of $1 \times 10^{10} \text{cm}^{-2}$ is reported. The mask for SAG was prepared with a newly developed atomic force microscope (AFM) nanolithography on carbonaceous films. The resolution of the mask openings could be as small as 26nm and ZnCdS/ZnMgCdS quantum dots defined by the mask openings were successfully grown selectively without lateral overgrowth. We demonstrate the selective area growth (SAG) of Zn(Mg)CdS dot-like structures in well-ordered arrays with densities as high as $1 \times 10^{10} \text{cm}^{-2}$. The mask used for SAG was a 2-3-nm-thick carbonaceous film deposited by electron-beam irradiation on a GaAs substrate and was patterned by anodization with the electric field applied between the AFM tip and the GaAs surface. The main factors determining the resolution in the AFM patterning were carefully studied and this allowed us to currently obtain dot-like patterns with the resolution of $\sim 26\text{nm}$ and the inter-dot distance of $\sim 100 \text{nm}$ in the masks ready for SAG. SAG was studied on (001) GaAs surfaces masked by the carbonaceous films by metalorganic molecular beam epitaxy. Nanoscale SAG in general faces the nucleation issues, but it was cleared by sulfurization of the GaAs surfaces and by the subsequent low-temperature initial growth of $\text{Zn}_{0.43}\text{Cd}_{0.57}\text{S}$ at the lower temperature of 300°C . The ZnCdS/ZnMgCdS heterostructures were grown at 380°C . The newly developed alloy of ZnMgCdS [2] and $\text{Zn}_{0.43}\text{Cd}_{0.57}\text{S}$ have the capability to lattice-match GaAs. The array of ZnCdS/ZnMgCdS quantum dots with the resolution of $\sim 26\text{nm}$, the size of which was defined by the mask opening, and with the density of $1 \times 10^{10} \text{cm}^{-2}$ was successfully grown with this method. The photoluminescence from the high-density dot array, recorded at 18K, was strong and showed a 6 meV blue-shift as compared with that from the unpatterned region. References: [1] E. Kuramochi, J. Temmyo, T. Tamamura, and H. Kamada, *Appl. Phys. Lett.* 71(1997) 1655. [2] A. Avramescu, A. Ueta, K. Uesugi, and I. Suemune, *J. Cryst. Growth* (to be published).

2:20 PM, II4 +

Fabrication of Nanometer-Scale InAs Quantum Structures by Electron-Beam Lithography and Reactive Ion Etching: Andy Cheng¹; *Chia-Hung Yang*¹; Ming-Jey Yang²; Doe Park²; ¹University of Maryland, Elect. and Comp. Eng., Rm. 1323, A.V.Williams Bldg., College Park, MD 20742 USA; ²Naval Research Laboratory, Washington, DC 20375 USA

Recently, there has been remarkable progress in the fabrication of quantum devices, whose dimensions are comparable to the Fermi electron wavelength. Most experimental efforts, however, has focused on

the GaAs-based heterojunction system, in which high-mobility two-dimensional electron gas is confined at the hetero-interface. The lateral size quantization effect is provided by a "split-gate" approach: patterned Schottky gates with a negative bias can deplete electrons below. Due to the Schottky barrier height and the material constants, the confining potential is smooth, resulting in disparity of the physical size and the dimension where electrons are located. For example, a GaAs quantum wire $\sim 500\text{nm}$ in width is already fully depleted of electrons. Furthermore, to substantiate quantum wave phenomena in the device characteristics, the device dimension should be less than the phase coherence length (L). Limited by electron-phonon and electron-electron scattering, L in high-electron mobility GaAs/AlxGa1-xAs heterojunctions is measured to be several microns at 4.2K. Our interest is to find an experimental system where many function quantum devices can fit into L . We have successfully developed in the InAs/AlxGa1-xSb system a fabrication process using electron-beam lithography (EBL) and reactive ion etching (RIE) for defining InAs quantum wires with 30nm minimal feature size, W_{min} . Typically, the sample consists of a S.I. GaAs substrate, a 2micron AlSb/GaSb superlattice buffer, a 12nm InAs quantum well, and a 12nm AlSb gate insulator. EBL using negative tone resist defines the etch-mask in the RIE process. As an example, we will report the observation of Aharonov-Bohm oscillations in the magnetoresistance of doubly connected InAs/AlSb rings with a diameter of 300nm and a wire width of 70nm. The ring's magnetoresistance shows strong periodic oscillations associated with the magnetic fluxes, h/e and $h/2e$ and $h/3e$, and the oscillations persist up to 7.6tesla without apparent decrease in amplitude. Such persistence, i.e., backscattering between edge states being unsuppressed by a high magnetic field, is owing to the narrowness of the InAs quantum wires. An L of approximately 1micron at 2.2K is experimentally obtained from the exponential decay of the harmonics in the Fourier power spectrum. This new InAs quantum wire system offers several unique advantages for studying quantum transport. First, the 1D wires have abrupt confinement both in the vertical and the transverse directions. Second, surface Fermi level pinning of InAs allows for the realization of 70nm nanostructures without the common problem of edge depletion for GaAs-based heterostructures. Finally, the observed L is 14 times of the quantum wire width, and 4 times of the inner diameter of the AB ring. Using our new fabrication technique, it is now possible to build a patterned, complicated quantum circuit within one coherence length.

2:40 PM, II5

InAs Dots Grown by MBE on InAlAs and InGaAs Lattice Mismatched Buffers on GaAs: *Yvon Cordier*¹; Denise Ferré²; Patrice Miska¹; ¹Institut d'Electronique et de MicroElectronique du Nord, Avenue Poincare BP 69, Villeneuve d'Ascq 59652 France; ²LSPES, Université de Lille 1, Villeneuve d'Ascq 59652 France

The self organization of InAs dots is a powerful tool for the realization of quantum devices. The way in which the 2D wetting layer becomes 3D and rearranges into dots involves strain as well as surface diffusion. Furthermore, in the case of the use of a matrix lattice mismatched to the substrate, other aspects like surface roughness (steps) and buried dislocations have to be investigated. In this work, we investigated the growth of InAs dots on GaAs substrates. Both thin pseudomorphic and thick composition graded strain relaxed (metamorphic) InAlAs and InGaAs layers were used as a template for the realization of the dots. The layers were grown by molecular beam epitaxy on exactly oriented (001) GaAs substrates; InAs films were deposited at 500°C . RHEED was used to observe the 2D-3D transition and the InAs covered surfaces have been investigated with scanning electron microscopy and atomic force microscopy. In the case of thin pseudomorphic layers used as a template, the 2D-3D transition occurs as for GaAs buffer layers due to similar in-plane lattice mismatch, but new arrangement of the InAs dots is observed when misfit dislocations are introduced into the template that overcomes its critical thickness (dot free regions and dot accumulation/coalescence regions). Thick composition graded buffer layers exhibit a typical cross-hatched roughness with main striations parallel to [1-10] direction. This pattern is usually explained by the anisotropy of surface diffusion and a sensitivity to the in plane residual stress of Indium adatoms and/or accumulation of steps due to buried dislocation pile-up. However the deposition of InAs on these buffer layers does not lead to a preferential nucleation of the dots at the top of the ridges as observed for thick InGaAs layers with uniform composition [K.Samonji et al. *J.Appl.Phys.* Vol.86, N°3 (1999)]. Nevertheless, alignment of dots is observed at the edge of steps generated

by the growth of the metamorphic buffer layer. Our results show a dependence of the density and the shape of the dots with the grading rate of Indium content in the buffer layer, attributed to the reduction of the strain when the buffer gets thicker (lower in-plane stress at the top of the template). The effect of lateral composition modulation at the surface of the template will be discussed. Furthermore, the dots elongates toward [1-10] when the final Indium content is increased from 33%, to 42% and 52%. Dots realized on the latter exhibit the same morphology as ones grown on a 52% In content buffer lattice matched to InP substrate and confirms that this effect is mainly due to a change in surface diffusion properties

Session JJ. Device Processing: Etching, Implantation, Oxidation and Passivation

Friday PM Room: Centennial Halls
June 23, 2000 Cafeteria

Session Chairs: Marian Hargis, Purdue University, West Lafayette, IN 47906 USA; Louis Guido, Virginia Technology University, Dept. Matls. Sci. and Eng., Blacksburg, VA 24061 USA

1:20 PM, JJ1 +

Low Damage and Selective Etching GaN over AlGaN for Gate-Recessing of AlGaN/GaN HFETs: *William B. Lanford*¹; Cathy Lee¹; Ling Zhou¹; Andrew Ping¹; Ed Piner²; Ilesanmi Adesida¹; ¹University of Illinois at Urbana-Champaign, Dept. of Elect. and Comp. Eng., 208 N. Wright St., Urbana, IL 61801 USA; ²Epitronics Corporation, 550 West Juanita Ave., Mesa, AZ 85210 USA

There is currently much interest in AlGaN/GaN HFETs for high power and high temperature applications. One of the factors that is currently limiting device performance is the resistance of the ohmic contacts placed directly on the AlGaN Schottky layer. High ohmic resistance is detrimental to device characteristics such as drain current, transconductance, and bandwidth. A recessed-gate structure, which allows for the source and drain ohmic contacts to be placed on a heavily doped n-GaN cap layer, has only recently begun to attract attention as nitride etching technology has become more mature. It is necessary to etch through a thin GaN cap layer without causing any damage to the structure. Additionally, it is desirable to stop etching on the underlying AlGaN layer, because overetching results in devices with non-uniform threshold voltages. To this end, it is important to develop a low-damage selective etch process that is appropriate for gate-recess etching in the fabrication of high-performance GaN/AlGaN HFETs. In this work, we have also studied the use of an ICP-RIE to selectively etch GaN over Al_xGa_{1-x}N (0.08 <x <0.40) and have studied ion-induced damage on GaN and AlGaN surfaces. By adding small amounts (<5%) of O₂ or SF₆ to the etch mixture (Cl₂/Ar), we form involatile AlO_x and AlF_x products on the AlGaN layer, which inhibit further etching and results in a selective etch process. In addition to gas flow rates, we have studied the effects of chamber pressure (2 to 10 mT), DC-bias (-50 to -150 V), and ICP power (200 to -600 W) on the etch rates and the selectivity of the etch as well as the surface morphology and etch profile. Selectivities ranging from ~10 to over 30 have been obtained for GaN over Al_xGa_{1-x}N with 0.08 <x < 0.40. These are the highest selectivities reported to date. Auger electron microscopy has been used to study etched surfaces in order to delineate suitable post-etch processes to restore GaN and AlGaN stoichiometries. Also, the effects of dry-etching on the electrical characteristics of GaN/AlGaN surfaces and heterostructures have been investigated using Schottky diode (I-V and C-V) and Hall measurements. These results will be presented along with a post-etch thermal-treatment which restores the Schottky diode characteristics without being detrimental to other aspects of the devices (e.g. ohmic contacts).

1:40 PM, JJ2 +

Chemically Assisted Ion Beam Etching of GaN-Based Waveguides and Photodectors: *Arkadi Goulakov*¹; Dinesh Patel¹; Carmen S. Menoni¹; John Torvik²; Jacques I. Pankove²; Paul G. Schroeder³; C. Brian France³; Bruce A. Parkinson³; ¹Colorado State University, Elect. and Comp. Eng. Depts., Fort Collins, CO 80523 USA; ²Astralux, Inc., 2500 Central Ave., Boulder, CO 80301-2845 USA; ³Colorado State University, Dept. of Chem., Fort Collins, CO 80523 USA

High-quality etching is essential when fabricating a variety of GaN-based devices. Etching vertical structures with smooth sidewalls and surface morphologies are required for optoelectronic devices such as laser diodes and waveguide structures. For electronic devices such as bipolar transistors and rectifiers it is critical that the etching does not create damage to critical areas of the device. Process-induced damage can lead to minority carrier recombination and premature breakdown. Different dry etching techniques have been developed for the nitrides, which due to high bond strengths exhibit considerably lower etch rates than GaAs and InP under the same conditions. In this paper we will discuss the results of Chemically Assisted Ion Beam Etching (CAIBE) etching of waveguides and photodectors fabricated on MOCVD grown GaN and show that near-vertical sidewalls of smooth morphology and low surface damage can be obtained at very low ion accelerating voltages. The waveguides structures were processed at a beam voltage of 250V, current density of 0.6mA/cm², and Cl₂ flows ranging from 0.5 to 10 sccm. While ion sputtering results in the appearance of ~0.1 mm defects on the etched surface and sidewalls of significant roughness, incorporation of Cl₂, as low as 1 sccm, significantly improves the sidewall morphology. Beyond 2 sccm near vertical profiles with smooth sidewall and minimum surface damage are obtained. At this flow rate, etch rates start to saturate. This behavior coupled with the linear dependence of the etch rate on ion beam voltage shows that the etch process is desorption limited. Auger spectroscopy analysis confirmed the presence of chlorine and an increase of the N/Ga ratio in the etched surfaces compared with as-grown surfaces. CAIBE was also used in the fabrication of GaN-based p-n photodiodes. These detectors exhibit a low leakage current density at < 40nA/cm² at -5V indicating minimal processing-induced damage. Furthermore, these diodes do not exhibit premature breakdown and have low leakage when tested up to -200V. This work is supported by CPOP and the State of Colorado.

2:00 PM, JJ3 +

Photoelectrochemical Selective Etching of AlGaN/GaN Device Structures: *Ting Gang Zhu*¹; Bryan S. Shelton¹; Ho-Ki Kwon¹; Damien J.H. Lambert¹; Michael M. Wong¹; Uttiya Chowdhury¹; Russell D. Dupuis¹; ¹The University of Texas at Austin, Microelect. Rsch. Ctr., PRC/MER-R9900, Austin, TX 78712-1100 USA

The etch selectivity of n-type materials over p-type layers and for GaN over Al_xGa_{1-x}N is an important aspect in the fabrication of many Al_xGa_{1-x}N/GaN based heterostructure devices. Most of the III-N device etching studies performed to date have focused on ion-assisted dry etching techniques. However, photoelectrochemical (PEC) etching has a potentially unique advantage in that it can be the basis of a selective etching process for the wide-bandgap nitrides. Furthermore, PEC is potentially able to provide a controllable, defect-free etching technology for these materials. We report here the dopant-selective and bandgap-selective PEC etching characteristics of GaN and AlGaN. The GaN and AlGaN heteroepitaxial films were grown in an EMCORE D125 UTM MOCVD reactor on c-plane sapphire substrates. We have successfully applied PEC etching to n-GaN/p-GaN, n-AlGaN/p-GaN, i-GaN/p-GaN and n-GaN/n-AlGaN for use in HBTs, HFETs, PIN photodetectors, and rectifier device structures. The results show great advantages over traditional dry etching techniques, including materials and dopant-type selectivity, low surface roughness, and sidewall anisotropy. In this work, we have employed the technique of immersing the sample in a beaker of KOH solution (at room temperature) and placing the beaker in an ultrasonic bath during PEC etching. We have recorded the photocurrent during the etching process and by monitoring the photocurrent vs. time profile, we can simply and accurately control the etching process. In our experiment, the samples were illuminated by a broad-spectral-range Hg/Xe arc lamp, and the samples were patterned by employing a thin evaporated Ti/Pt film as an etch mask to ensure good electrical contact to the material and to block the UV light. We have studied the characteristics of PEC etching under a variety of conditions. We have found that ultrasonically-aided PEC etching greatly improves the surface morphology, and also helps in reducing

the commonly observed non-uniformity of the etch rate. We have demonstrated etch rates ~ 20 nm/min with a KOH solution of 0.015 M and an intensity of 15 mW/cm². Furthermore, an ultra-smooth RMS roughness of 0.946 nm was obtained, better than that of RIE, which was 0.981 nm for the same n-GaN layer. This low surface roughness is the best reported to date for PEC-etched surfaces and demonstrates a new way to achieve device-quality etched layers over a large area. We will also report the effect of varying the wavelength and illumination intensity of the ultra-violet light, the Al alloy composition, the electrolyte concentration, layer doping level, and film quality on the selectivity, layer-stopping capability and surface roughness. This technique has demonstrated great promise in the group III-nitrides and adds additional flexibility to the processing and growth procedures required for the development of high-performance III-N devices.

2:20 PM, JJ4 +

Index Guided II-VI Lasers with Low Threshold Current Densities: *Matthias Strassburg*¹; Oliver Schulz²; Udo W. Pohl¹; *Marius Grundmann*¹; Dieter Bimberg¹; Satoshi Itoh²; Kazushi Nakano²; Akira Ishibashi²; Matthias Klude³; Detlef Hommel³; ¹TU Berlin, Institut für Festkörperphysik, Sekr. PN5-2, Hardenbergstr. 36, Berlin 10623 Germany; ²Sony Corporation, Shinagawa-Ku, Tokyo 141-0001 Japan; ³Universität Bremen, Institut für Festkörperphysik, Kufsteiner Str. NW1, Bremen 28359 Germany

Green semiconductor lasers are essential to realise many new optoelectronic display systems like laser TV. The ZnSe-system has already proven its potential for laser diodes in the spectral range of 490-530 nm. The lifetime of such laser diodes is about 400 hours in cw-operation and the present record threshold current density is 176 A/cm². Further progress is indispensable before such devices can be commercialised. In this contribution we present implantation induced disordering (IID) as a powerful tool to improve dramatically the laser characteristics. The vertical intermixing of masked layers upon IID generates a lateral step of the index of refraction and the specific resistance leading to an efficient lateral guiding of the injection current and the light wave. For II-VI materials the generation of vacancies by ion implantation was shown to increase the Cd diffusion in the intermixed layers of a laser structure. This leads to a sufficient change of the index of refraction. Hence the lasers become index guided instead of gain guided. To generate an effective intermixing of the laser structure, the energy of the implanted ions must be adjusted to create the maximum of vacancies in the vicinity of the active region. Therefore, we used 40Ar⁺ ions with a dose of $1 \cdot 10^{15}$ /cm² and 15N₂⁺ ionised molecules with a dose of $5 \cdot 10^{14}$ /cm² for implantation. The accelerating voltage was 2.5 MV in both cases. A dramatic decrease of the threshold current density by factor of three from 276 A/cm² to 96 A/cm² for ZnCdSe laser diodes and from 447 A/cm² to 153 A/cm² for ZnCdSse laser diodes was achieved. The same factor was obtained for an index guided laser grown by selective epitaxy demonstrating the high efficiency of the implantation induced intermixing. To realise a fast implantation process we developed a multilayer lithography method. Thus, time extensive energy switching for different layer thicknesses is no longer necessary. The reduced threshold current density leads to improved emission characteristics. TEM00 emission was observed for lasers with a stripe width up to 20µm. Even for drive currents seven times above the threshold no higher modes occur. Hence laser emission becomes largely independent from the injection current. Furthermore, the differential quantum efficiency increases by a factor 2-3 and cw-lifetimes 2-5 times longer than for gain guided structures are observed. These results prove the potential of the IID technology to realise long living green semiconductor lasers.

2:40 PM, JJ5 +

Comparative Studies of Thermal Oxidation of Sacrificial Silicon on 4H-SiC Epilayer: *Adrian C. H. Koh*¹; Angela Kestle¹; Gareth Pope¹; S. P. Wilks¹; P. A. Mawby¹; ¹University of Wales Swansea, Elect. and Electro. Eng., Singleton Park, Swansea, Wales SA2 8PP UK

The quality of thermally grown oxide on Silicon Carbide has always been an issue, hindering the reproducibility of reliable Silicon Carbide based power devices. This is primarily due to the inert properties of SiC material that makes it difficult to yield an oxide of acceptable quality, in particular the SiC/SiO₂ interface. Recent reports have displayed tremendous progress in achieving thermally grown oxide layers with an interface states density equivalent to that observed in Silicon technology. However much of the research work regarding oxidation on sacrificial Silicon

produced a lack of promising results. This paper shows a comparative study of thermal oxidation of sacrificial Silicon deposited at different temperature on SiC and by controlling the oxidation temperature hence preventing the diffusion of SiO₂ into the SiC substrate. This approach was carried out focusing on the critical aspect of surface preparation, Si/SiC interface and the oxidation conditions. In this work, an n-type 4H-SiC with 10mm thick n-type epilayer doped at 1.1×10^{16} cm⁻³ was used. An RCA clean and heat treatment, under a UHV environment, were performed as a form of surface preparation to remove contaminants and possible graphite on the wafer. Silicon was then evaporated under UHV condition at room and elevated temperature of 350°C to form a layer approximately 30nm thick. The sample was extracted and dipped into BHF to remove the oxide that was formed during the extraction from the UHV chamber, before transferring the sample into the furnace. By controlling the oxidising temperature we are able to limit the oxidation process to only oxidise the Si layer. A wet re-oxidation anneal (ROA) was performed to further improved the SiO₂/SiC interface. Measurements were applied to characterize the oxide quality.

3:00 PM Break

3:40 PM, JJ6 +

Use of Dual Sided Controlled Oxidation to Produce Ultra Thin Silicon on Insulator or Silicon on Air Membranes Formed by Epitaxy Techniques: *Steve Bourland*¹; Sangwoo Lee¹; Rashid Bashir¹; John P. Denton¹; Gerold W. Neudeck¹; Mark S. Lundstrom¹; ¹Purdue University, Elect. and Comp. Eng. Depts., 1285 EE Bldg., W. Lafayette, IN 47906 USA

Motivation: There has been much research into ways to fabricate Silicon-on-Insulator (SOI) devices, with a recent thrust towards ultra-thin SOI devices. These SOI devices show improved performance and reduced degradation to hot carrier immunity, among other advantages. A complementary research direction being pursued is also the use of low K dielectric for reduced capacitances at appropriate locations in the device. Variety of SOI approaches have been described in literature including SIMOX, bonded etched back SOI, Selective Epitaxial Growth, etc. Many of these schemes do not directly lend themselves to form ultra thin SOI layer (< 10nm in thickness). We propose the use of controlled low temperature dual sided oxidations of SOI layers to form ultra-thin SOI layers. This approach is compatible with other SOI approaches with the addition of a Selective Epitaxial Growth of Silicon, which is needed to 'anchor' the SOI layers to the substrate. The purpose of this paper is to present initial experimental results to demonstrate the formation of these membranes, and also the controlled reduction of their thickness. Experiments & Results: Use of selective epitaxial growth of silicon as well as controlled oxidation techniques can lead to a relatively simple process for the formation of arbitrarily thin silicon membranes on either an insulating layer, or vacuum, depending on the application. Selective epitaxial growth in combination with chemical-mechanical polishing (CMP) allows the formation of silicon membranes on the order of 150 nm. Controlled oxidation can then be used to thin the silicon membranes to an arbitrary thickness, on the order of 10 nm. The process began by growing a field oxide and etching a window to define the location of the membrane. Another oxidation step was then performed to grow an oxide in these openings. The initial membrane thickness was defined by the difference between the final field oxide thickness and the oxide grown by the 2nd oxidation step. Four seed holes of approximately 5mm diameter were defined and etched using reactive ion etching within each of the membrane areas. A short annealing oxidation and wet etch is then performed prior to the epitaxial growth. SEG silicon was grown from the seed-holes at 970°C, 40T using DCS and HCl in a pancake type reactor. The SEG silicon growth merged from the seed-holes and was subsequently planarized using chemical-mechanical polishing with the field oxide as an etch stop, forming the initial SOI membranes. The oxide underneath the silicon membranes is then stripped off to leave the diaphragms suspended in air. Subsequent oxidation steps are then performed to thin the membrane to a desired thickness for specific applications. Cross sectional SEMs and TEMs will be presented showing the initial results and the controlled thinning of the silicon membranes.

4:00 PM, JJ7

Characterization of UV-Ozone Oxidized InGaAs/InP Heterostructures: *R. Driad*¹; Z. H. Lu¹; W. R. McKinnon¹; S. Moisa¹; S. P.

McAlister¹; ¹National Research Council, IMS-M50, Montreal Rd., Ottawa, Ontario K1A 0R6 Canada

Although the surface recombination of InGaAs is low, it is still large enough to degrade the performance in InP-based devices such as InGaAs/InP photodiodes and heterojunction bipolar transistors (HBTs). Passivation treatments are needed to reduce the recombination, but these treatments must not degrade the electrical characteristics, even if a layer of dielectric is deposited to protect or isolate the device. In this work, we evaluate the combination of ultraviolet (UV) radiation and ozone for passivating InGaAs/InP HBTs. The UV-ozone technique is widely used to clean organic contaminants from semiconductor surfaces. It has been successfully used to produce uniform thin films of stoichiometric native oxides, which can be used as sacrificial layers to protect semiconductor surfaces before the growth or regrowth of epitaxial layers. It has also been suggested that oxides created by UV-ozone can also passivate the surface of electronic devices such as FETs and HBTs, or separate the semiconductor surface from dielectric coatings. The aim of this work is to study how UV-ozone oxidation, intended to passivate the InGaAs extrinsic base, affects the adjacent semiconductor layers of InP-based HBTs. We report the electrical characteristics of devices treated with UV-ozone, and we present data from x-ray photoelectron spectroscopy (XPS) showing the composition and thicknesses of the oxides created. We found that the UV-ozone treatment not only produces a surface oxide film, but also produces after about 10 minutes a stoichiometric semiconductor surface. Longer treatments, however, produce nonstoichiometric surfaces. The characteristics of HBTs reflect the surface composition; the current gain of HBTs treated with UV-ozone first increases with exposure time, reaching a maximum after 10-15 minutes, then decreases for longer exposures. The current gain measured at 1 mA improves by a factor of 3 after 10 minutes of treatment, due to a decrease in the base leakage current. On the other hand, the UV-ozone treatment drastically degrades other characteristics of the device. Base-collector leakage currents are noticeably higher, and breakdown voltages lower, in all samples treated for more than 2-3 minutes, both in single HBTs with InGaAs collectors and double HBTs with InP collectors. This contrast in the changes of gain and breakdown might be due to different oxidation mechanisms between the planar intrinsic base and the vertical base-collector sidewalls. Recent studies on thermal oxidation of III-V heterostructures containing Al showed that oxides formed during lateral oxidation of vertical sidewalls are generally thicker than those formed on horizontal surfaces. Our results show that a tradeoff between gain and breakdown must be made in UV-ozone treatment, since a treatment brief enough to avoid degrading the breakdown voltage is too short to optimize the current gain.

4:20 PM, JJ8 +

Fabrication of InP Metal-Insulator-Semiconductor Structures Using BaTiO₃ as an Insulating Layer: R. R. Sumathi¹; N. V. Giridharan¹; J. Kumar¹; ¹Anna University, Crystal Growth Ctr., Chennai 600 025 India

Opto-electronic telecommunication technology is based upon crystalline materials of III-V semiconductors (GaAs, InP, GaN, InSb, etc.). Among the III-V compound semiconductors, InP is the potentially attractive material for the development of high-speed, high power devices and opto-electronic integration because of the high values of saturation current, breakdown voltage, thermal conductivity and radiation resistance. Fermi-level pinning and very high leakage current at the metal-InP interface due to surface states is one of the biggest obstacles which impede the development of InP based Metal-Semiconductor (MS) devices. Hence InP based Metal-Insulator-Semiconductor (MIS) structures are widely studied. The MIS capacitor is the most powerful tool for investigating all the electrical properties of the semiconductor surface. The performance of the MIS diode is controlled by the electronic interaction at the oxide-semiconductor interface. Finding more suitable (insulating) material with high resistivity and high stability is essential for the fabrication of InP based MIS devices. Two main methods are used to realise the insulating layer of InP (i) native oxide growth on InP (ii) deposition of an insulating layer such as SiO₂, Si₃N₄, Al₂O₃ etc. The disadvantage of the insulator deposition is the thermal damage caused during deposition. In thermal oxidation, the surface state density obtained is quite high and is of the order of 10¹³ eV⁻¹ cm⁻². Instability upon exposure to a water-containing ambient and/or a slightly elevated temperature is the problem to be overcome with anodic oxides on InP. Hence, to overcome the problems related to the insulator deposition on InP, an attempt has been made to

find a suitable insulating material, which could be deposited at room temperature and have high resistivity and stability. In this work, Barium Titanate (BaTiO₃), a dielectric material is proposed as a new insulating material for InP MIS structures due to its high dielectric constant, low leakage current and high electric field strength. BaTiO₃ thin films have been deposited on InP substrates using sol-gel technique through organic precursor route. The precursor solution was coated on InP substrate by spin coating method. As-deposited BaTiO₃ films by sol-gel technique are amorphous in nature and post-deposition annealing yields polycrystalline films. XPS results confirmed the formation of BaTiO₃ on InP substrates. MIS (MOS) structures were fabricated on the deposited BaTiO₃ thin films. Capacitance-Voltage measurements were carried out on the fabricated MIS structures. The shift in the C-V curve towards the positive side shows the presence of negative fixed charges at the oxide near the interface. Minimum hysteresis width of 0.5V is obtained for the BaTiO₃/InP MIS structures, indicating high resistivity and stability of the BaTiO₃ insulating layer. The minimum surface state density value as low as 6x10¹⁰ cm⁻² eV⁻¹ has been obtained for Au/BaTiO₃/InP MIS structures and is comparatively less than that of other deposited insulators. The Deep Level Transient Spectroscopic (DLTS) studies were carried out on the fabricated MIS structures. The results will be presented in detail.

4:40 PM, JJ9

Investigations on the Proton Irradiation Induced Defects on Ni/n-GaAs Schottky Barrier Diodes: P. Jayavel¹; K. Santhakumar²; P. Magudapathy²; J. Kumar¹; ¹Anna University, Crystal Growth Ctr., Chennai 600025 India; ²IGCAR, Matls. Sci. Div., Kalpakkam 603102 India

Implantation in III-V semiconductors is widely used for the fabrication of monolithic integrated devices and electronic devices for digital and microwave applications. Irradiation of the semiconductors with an ion beam introduces electrically active defects, which change the property of the material at the surface or deep into the surface depending upon the energy of the ion. Low energy and high dose ion irradiation are of much of interest to design ultra large scale integrated circuit. The low energy light ion irradiation provides a way to control the depth distribution of recombination centers. Localized layers with a high density of lifetime killers can be created at any depth within the active layer of the devices by varying the ion energy. The defects created in the low energy irradiated material are as a result of nuclear stopping due to elastic collisions with the target atoms. The defects act either as traps or as recombination centers in the semiconductors depending on the capture cross section of the electrons and holes. Traps reduce the semiconductor free carrier density whereas recombination centers introduce generation-recombination current in rectifying devices. Hydrogen in semiconductors has received widespread attention for its ability to passivate dangling bonds and bond defects and to neutralize acceptor and donor activity. Proton ion irradiation of GaAs can also be used to create high resistivity regions for electrical isolation in devices and integrated circuits. It has been found that proton irradiation in metal/semiconductor interface interacts with defects to passivate them and improve the device performance. In view of the potential applications of proton irradiation in GaAs device fabrication, it is of interest to investigate the proton irradiation induced defect centres and to study their effect on the performance of the Schottky Barrier Diodes (SBDs). For our present investigations, the SBDs have been fabricated on LEC grown silicon doped (n=2x10¹⁶ cm⁻³) GaAs substrates. Au/Ge/Ni ohmic contact of thickness 2500 Å was realized on the back side of the substrate and then annealed at 703K for 5 minutes under high pure argon atmosphere. Circular nickel (Ni) Schottky contact of thickness 2000 Å and of area 7.86x10⁻³ cm² has been deposited on the polished surface through a metallic mask using an electron beam evaporation system under a vacuum of 2x10⁻⁶ mbar. Ni/n-GaAs Schottky Barrier Diodes have been irradiated using low energy proton ions of fluences 1x10¹⁴, 1x10¹⁵ and 1x10¹⁶ p/cm² to study the effect of irradiation damages very close to the interface. Proton irradiations have been carried out at room temperature using a 150 keV accelerator at a background pressure of the order of 8x10⁻⁷ mbar. Low energy (50 keV) proton irradiation was chosen in such a way that the irradiation induced defects have been uniformly introduced in a controlled manner at the interface and within the depletion layer of the Ni/n-GaAs Schottky barrier. The irradiated SBDs were annealed at 573 and 673K for 5 minutes under high pure argon atmosphere. Current-Voltage (I-V) measurements of the SBDs were carried out under dark conditions and Capacitance-Voltage (C-V) measurements were carried out at room temperature using an automated system of 1 MHz Boonton 7200 capacitance meter. We have observed that the

change in the reverse leakage current increases with increasing ion fluences. The barrier height of the SBDs has been found to decrease and the ideality factor deviates from the ideal behavior with increasing ion fluences. This non-rectifying behavior is due to the irradiation induced defects at the interface. The rectifying behavior of the SBDs improved, upon annealing at 573 and 673K. The capacitance value of the irradiated diodes has been found to be less than the control diodes and it increases with increasing ion fluences. The capacitance of the irradiated and annealed diode decreases for all fluences due to the removal of the irradiation induced carriers at the interface. The carrier concentration reduces by the proton irradiation through the mechanism of passivation and defects trapping at the interface and within in the depletion region. An extensive investigations on the Current-Voltage and Capacitance-Voltage characteristics of the low energy (50 keV) proton irradiation (fluence of 1×10^{14} , 1×10^{15} and 1×10^{16} p/cm²) induced defects on the Ni/n-GaAs Schottky Barrier Diodes (SBDs) and the effect of annealing will be presented in detail.

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