1999 EMC At-A-Glance

Wednesday Morning, June 30, 1999

8:30 AM   **EMC PLENARY LECTURE/STUDENT AWARDS**

Room: **Corwin Pavalion**

Plenary Speaker: **Shuji Nakamura, Nichia Chemical Industries, Ltd., R&D Dept., 491, Oka, Kaminaka Anan, Tokushima Japan**

Topic: **"Present and Future Prospects of InGaN-Based Blue LEDs and LDs"**

Break: **9:30 AM - 10:00 AM**

Session A. Semiconductor Quantum Dots - Devices
Room: Multicultural Center Theater

10:00	A1, Gain and Emission Characteristics of MOVPE Grown InP/GaInP Quantum Dot Lasers .... Thomas Riedl
10:20	A2, 4 Watt High Power Quantum Dot Lasers .... M. Grundmann
10:40	A3, Electroluminescence of Stacked In(Ga)As/GaAs QDs at 1.3 mm - 1.4 mm .... Frank Heinrichsdorff
11:00	A4, Collisional Carrier Kinetics and Broadening of Spectral Lines Quantum Dot Structures .... Alexander V. Uskov
11:20	A5+, Direct Bandgap Materials for Monolithic Optical Interconnects on Silicon .... Victoria Ann Williams
11:40	A6, Late News

Session B. Materials Integration - Substrate Fabrication and Bonding
Room: State Street

10:00	B1+, Fabrication of Thin Film InGaN LED Membranes by Laser Liftoff .... William S. Wong
10:20	B2+, GaN LEDs Transferred to Copper Substrates Using Laser Assisted Debonding .... Philip R Tavernier
10:40	B3+, A Comparison of Wet and Dry Chemistries for Hydrophobic Silicon Wafer Bonding .... James B. Mattzela
11:00	B4+, Deposition of Borosilicate Glasses by Low Pressure Chemical Vapor Deposition Using Tetraethylorthosilicate and Trimethylborate .... Darren Michael Hansen
11:20	B5, Ion-cutting of GaSb Wafers .... Y. Zheng
11:40	B6, Late News

Session C. Characterization, Growth and Properties of Organic Electronic Materials
Room: Santa Barbara Harbor Room

10:00	C1, Dependence of Emission Quantum Yield on Chain Packing in Electroluminescent Polymers .... Lewis J. Rothberg
10:20	C2+, Near-Field Scanning Optical Microscopy of Conjugated Polymer Films .... Jessie A. DeAro
10:40	C3, CPAFM: A Tool for Nanoscale Structure and Electronic Properties .... Tommie Wilson Kelley
11:00	C4+, Growth of Thermally Evaporated Pentacene Films on SiO2 .... Jonathan Andrew Nichols
11:20	C5, Nanoscale Investigation of the Optical Properties of Tris-8-Hydroxyquinoline Aluminum Films (Alq$_3$) .... Grace M. Credo
11:40	C6, Late News

Wednesday Morning (Cont'd)

Session D. Oxides for Devices
Room: Flying A Studios

10:00   **D1+, Increased Lateral Oxidation Rates of AlInAs on InP Using Short-period Superlattices**
.... Eric Hall

10:20   **D2+, As Overpressure Mediated Crystallinity Change of AlGaAs Compounds and its Application in Formation of Bragg Reflectors**
.........................Kuo-Lih Chang

10:40   **D3+, The Effect of an Oxide Aperature on the Base-Collector Capacitance of a GaAs Heterojunction Bipolar Transistor**
.........................James G. Champlain

11:00   **D4+, Electrical Properties of Al2O3 Gate Dielectric**
.........................Chin Chang Liao

11:20   **D5, Late News**

11:40   **D6, Late News**

Session E. Special Topical Session
Room: Lotte Lehman Hall

1:30   **E1*, Electron Microscope Studies of Defects, Piezoelectric Fields and Microscopic Luminescence in InGaN/GaN Films**
.... D. Cherns

2:00   **E2*, The Technological Significance of Defects in III-Nitride Materials**
.... S. Jeffrey Rosner

2:30   **E3*, GaN Lateral Epitaxial Over Growth (LEO) on Silicon and Sapphire Substrates**
.... S. P. Denbaars

3:00   **E4*, Effect of Native Point Defects on Nitride Materials and Devices**
.... Chris G. Van de Walle

3:30   **Break**

3:50   **E5*, The Effect of Doping and Growth Stoichiometry on the Properties of Threading Dislocations in GaN**
.... Alan F. Wright

4:20   **E6*, Effects of Point Defects and Dislocations on Transport Properties of GaN**
.... David C. Look

4:50   **E7*, Lateral and Pendeo-Epitaxial Overgrowth and Defect Reduction of GaN Films**
.... Robert F. Davis

5:20   **E8*, Characterization of Nitride Semiconductor Heterostructures and Laser Diodes**
.... D. P. Bour

Session F. Semiconductor Quantum Dots - Formation and Structure
Room: Multicultural Center Theatre

1:30   **F1, Infrared Spectroscopy of Intraband Transition in Modulation Boron-Doped GeSi Quantum Dot Superlattices**
.... Wen Gang Wu

1:50   **F2, Study of Phonons in Self-Organized Multiple Ge Quantum Dots**
.... Jianlin Liu

2:10   **F3, Raman Spectroscopy of the Topology of the InAs/GaAs Self-Assembled Quantum Dots**
.... Yuri Alexander Pusep

2:30   **F4, Microscopic Transient Photoluminescence of Site-Controlled InAs Dots**
.... Tetsuya Nishimura

2:50   **F5, Optical Properties of InAs/InP Self-Assembled Quantum Dots Grown by Metalorganic Chemical Vapor Deposition**
.... Euijoon Yoon

3:10   **Break**

3:30   **F6, Fluorescence Intermittency and Quantum Efficiency of Individual Silicon Nanoparticles**
.... Michael D. Mason

3:50   **F7, Origin of Size Distribution in ZnSe Self-Organized Quantum Dots Grown on ZnS layers**
.... Takehiko Tawara

4:10   **F8, Structural Studies of Stacked InAs Quantum Dots in a Silicon Matrix Grown by MBE**
.... N. D. Zakharo

4:30   **F9, In-Situ Self-Organization of Two- and Three-Dimensional High-Density InAs Quantum Wire Arrays on (100) InP**
.... Hanxuan Li

4:50   **F10, Late News**

1999 EMC At-A-Glance

Wednesday Afternoon, June 30, 1999

Session G. Epitaxy for Devices
Room: State Street Room

1:30 G1, Tellurium Memory Effects on OMVPE-grown In0.3Ga0.7As0.997N0.003/GaAs Laser Diodes
.... Nein-Yi Li

1:50 G2+, Investigation of p-type GaInNAs for Heterojunction Bipolar Transistor Base Layers
.... Huoping Xin

2:10 G3+, Growth and Characterization of Long Wavelength (1 micron) GaInAsN Photo-detectors using Gas Source Molecular Beam Epitaxy
.... Sudhir G. Subramanya

2:30 G4, InGaAsN for High Efficiency Solar Cells Grown by Metalorganic Chemical Vapor Deposition
.... Andrew A. Allerman

2:50 G5, Late News

3:10 Break

3:30 G6+, AlGaAs and InGaAs-based Light Emitters on Si via Relaxed Graded GeSi Buffer Layer
.... Michael E Groenert

3:50 G7+, Lattice Matched $Zn_xBe_{1-x}Te$ Films with GaAs and ZnSe for p-Contact Layers of ZnSe-Based II-VI Laser Diodes
.... M. W. Cho

4:10 G8, Selective InAs Contact to GaAs
.... Kumar Shiralagi

4:30 G9+, Development of Multi-functional InGaAs-based Ohmic Contacts for GaAs Devices
.... Mitsumasa Ogura

4:50 G10, Use of Multi-quantum Wells for Photoabsorption Enhancement in Compound Semiconductor Solar Cells
.... Yoshitaka Okada

Session H. Electronic Transport in Organic & Molecular Materials
Room: Santa Barbara Harbor Room

1:30 H1*, What Determines the Resistance of a Molecule?
.... Supriyo Datta

2:10 H2, Simulation of Molecular Devices from First-Principles
.... Massimiliano Di Ventra

2:30 H3+, Electronic Transport Characteristics Through Diisocyanide
.... Jia Chen

2:50 H4, Improved Contacts for Organic Electronic Devices Using Self-Assembled Charge Transfer Materials
.... Jianna Wang

3:10 Break

3:30 H5*, High Mobility Charge Transport in Aromatic Hydrocarbon Single Crystals
.... Jan Hendrik Schön

4:10 H6, High Mobility Polymer Thin Film Transistors Based on Copolymers of Thiophene and 3-Hexylthiophene
.... Jianna Wang

4:30 H7+, Contact Limited Performance of Pentacene Thin Film Transistors
.... David J. Gundlach

4:50 H8, Late News

Session I. Column IV Heterostructures and Devices
Room: Flying A Studios

1:30 I1+, Exploitation of Facet Formations in SiGe/Si Selective Epitaxial Growth for Achieving a Nanometer Template
.... Greg D. U'Ren

1:50 I2+, Selective Si Epitaxial Growth Using Ultrathin Oxide Mask Formed By Resistless Patterning
.... Shawn G. Thomas

2:10 I3, Electrical and Structure Characterization of Single Crystalline SiGe Formed by Ge Deposition and RTP
.... Y. H. Wu

2:30 I4, Surfactant Mediated Epitaxy of Ge/Si Heterostructures for Device Applications
.... Karl R. Hofmann

2:50 I5+, Direct Growth of Ge on Si for Integrated Si Microphotonic Photodetectors
.... Hsin-Chiao Luan

3:10 Break

3:30 I6+, Boron Segregation in Polycrystalline $Si(1-x-y)Ge(x)C(y)$ Alloys
.... Eric Jonathan Stewart

3:50 I7, X-Ray Diffraction and Transmission Electron Microscopy Study of the Development of Texture in Polycrystiallin $Si_{1-x}Ge_x$ Thin Films
.... Wei Qin

4:10 I8, Diamond Epitaxy for Electronic Devices
.... Aleksandar Aleksov

4:30 I9+, Epitaxial Growth of $Si/Y_2O_3/Si$: A Potential SOS Structure
.... Michael Edward Hunter

4:50 I10, In Situ Observation of Epitaxial Co Silicidation on Si(001)
.... Kunihiro Sakamoto

Session J. Epitaxy for Devices

Room: Corwin East

8:20	**J1+, DC Charaterization of Annealing Effect on the Carbon Doped Base of InGaP/GaAs HBTs Grown by LP-MOCVD** .... Qinghong (Jack) Yang
8:40	**J2, Effect of High-Temperature Annealing on Device Performance of GaInP/GaAs HBTs Grown by LP-MOVPE** .... F. Brunner
9:00	**J3, Low Resistance Visible Wavelength Distributed Bragg Reflectors** .... J. M. Fastenau
9:20	**J4, High P-type Doping in InAlP Grown by Metalorganic Chemical Vapor Deposition** .... Yuichi Sasajima
9:40	**J5+, Growth and Characterization of InAlGaP Superlattice Lasers** .... Richard D. Heller
10:00	**Break**
10:20	**J6, Device Quality, Bandgap Engineered InAs-Channel Fet Material Structures** .... Leye A. Aina
10:40	**J7, Transport Properties of InAs Layers Grown on GaP Substrate by MBE** .... E. H. Chen
11:00	**J8, Effects of HEMT Pseudomorphic Channel Material Design on Device Performance** .... Yaochung Chen
11:20	**J9, Growth of High-Performance InP IMPATT Diodes by Metalorganic Chemical Vapor Deposition** .... Ho Ki Kwon
11:40	**J10, Late News**

Session K. Nanoscale Characterization

Room: Corwin West

8:20	**K1+, Nanoscale Charge Transport Properties of Co/SiO_2 Multilayer Structures and Their Application in a Novel Magnetic Field Sensor** .... Daniel M. Schaadt
8:40	**K2, Novel Application of Kelvin Force Microscopy** .... Rafi Shikler
9:00	**K3, +InGaAs/InP Quantum Well Intermixing Studied by Cross-sectional Scanning Tunneling Microscopy** .... Huajie Chen
9:20	**K4, Ordering-Induced Band Structure Effects in GaInP Studied by Ballistic Electron Emission Spectroscopy** .... Michael Kozhevnikov
9:40	**K5, Late News**
10:00	**Break**
10:20	**K6, +Nanoscale Characterization of Stresses in Semiconductor Devices** .... James John Demarest
10:40	**K7, Extending Lateral Composition Modulations in InAs/AlAs Superlattices with Miscut Substrates** .... David M. Follstaedt
11:00	**K8+, Non-Alloyed Ohmic Contact on GaAs at Nanometer Scale** .... Takhee Lee
11:20	**K9, Nanomagnetic and Superconducting Properties of Self-assembled Quantum Dots** ....Supriyo Bandyopadhyay
11:40	**K10, Late News**

Session L. Wide Bandgap AlGaN/GaN Heterostructures

Room: Lotte Lehman Hall

8:20	**L1, Stress/Strain during MOCVD of AlGaN/GaN on LT GaN/AlN Buffers** .... Jung Han
8:40	**L2+, Local Electronic Structure of AlGaN/GaN Heterostructures Probed by Scanning Capacitance Microscopy** .... Kurt V. Smith
9:00	**L3, Polarization Fields in AlGaN/GaN Heterojunctions** .... James Paul Ibbetson
9:20	**L4+, Surface Potential Effects Due to the Piezoelectric Charge Associated with Dislocations in GaN** .... Changchun Shi
9:40	**L5, Two Dimensional Electron Gas Density and Polarization Effects in AlGaInN/GaN Heterostructures** .... J. W. Yang
10:00	**Break**
10:20	**L6+, Growth and Characterization of AlGaN/GaN Heterostructures** .... Christopher J. Eiting
10:40	**L7, Effect of Surface Roughness on Electron Mobility in AlGaInN/GaN Heterostructures** .... Asif Khan
11:00	**L8+, High Electron Mobility 2DEG in AlGaN/GaN Structures** .... Chris R. Elsass
11:20	**L9, Correlation Between Material Quality and Low-Frequency Noise Level in GaN Heterostructure Field Effect Transistors** .... Alexander A. Balandin
11:40	**L10, Characterization of GaN MIS Structures** .... Tamotsu Hashizume

10:00 AM +
Fabrication of Thin Film InGaN LED
Membranes by Laser Liftoff: *William S...*

1999 EMC At-A-Glance
Thursday Morning, July 1, 1999

Session M. SiC Growth & Characterization

Room: Multicultural Center Theater

8:20	**M1+, Formation of Macrodefects in SiC Physical Vapor Transport Growth** .... Edward Kyle Sanchez
8:40	**M2, Local Epitaxy and Epitaxial Laterial Overgrowth of SiC** ....Igor Ivanovich Khlebnikov
9:00	**M3, Susceptor Effects on 4H-SiC Epitaxial Growth** .... Barbara E. Landini
9:20	**M4, Epitaxial Growth of 6H-SiC on Spherically Polished 6H-SiC Substrate Using $Si_2Cl_6 + C_3H_8 + H_2$ by CVD** .... Shigehiro Nishino
9:40	**M5+, Crystalline Quality and Polytype Formation of SiC Films Grown with Different Concentrations of Ge on (111) Si Substrates** .... Wendy L. Sarney
10:00	**Break**
10:20	**M6, Deep Donor in Bulk n-type 4H-SiC** .... W. C. Mitchel
10:40	**M7+, Radiotracer Spectroscopy on Ta Related Deep Levels in 4H-SiC** ....Joachim Kurt Grillenberger
11:00	**M8, Effect of NO Annealing Conditions on Electrical Characterization of n-type 4H-SiC MOS Capacitors** .... Huifeng Li
11:20	**M9, Late News**
11:40	**M10, Late News**

Session N. Infrared Materials and Devices

Room: State Street Room

8:20	**N1, Influence of Interfacial Layers on GaAsSb/InP Heterostructures** .... Simon P. Watkins
8:40	**N2, MOCVD Growth of InAsSb/InPSb SLS's for Use in Infrared Emitters** .... Robert M. Biefeld
9:00	**N3+, MBE Growth of High Quality InGaAsSb/AlGaAsSb Heterostructures Using the Digital Alloying Technique** .... C. Mourad
9:20	**N4, InSb Based Mid-IR Light Emitting Diodes and Lasers** .... Tim Ashley
9:40	**N5, New Techniques for Epi-Down Mounting of Mid-IR Type-II Quantum-Well Lasers** .... Edward Hugh Aifer
10:00	**Break**
10:20	**N6, Linewidth Enhancement Factor in Mid-Infrared Semiconductor Laser Active Regions** .... Michael E. Flatte
10:40	**N7+, Carrier Recombination Eynamics of InGaSb Under Picosecond Free-Electron Laser Excitation** .... R. T. Kotitschke
11:00	**N8, Optical and Structural Studies of InAsSb/AlInAsSb Quantum Wells for Use in MID-IR Lasers** .... Philip D. J. Calcott
11:20	**N9, Fabrication of a 3-D Simple Cubic Infrared Photonic Crystal** .... Lisa Zavieh
11:40	**N10, InXGa1-xAs/AlyGa1-yAs/AlzGa1-zAs Asymmetric Step Qqantum Well Mid-Infrared (3-5.3um) Detectors:** .... Wen Gang Wu

Session O. Issues for Ferroelectric and High Permittivity Thin Film Materials

Room: Santa Barbara Harbor Room

8:20	**O1*, Modeling of Oxide Materials for Memory Applications** .... Rainer Waser
9:00	**O2, The Effect of Thickness on the Dielectric Properties of Thin Epitaxial Films of BaTiO3** .... Soma Chattopadhyay
9:20	**O3, Non-Stoichiometry Accommodation and Properties in $(Ba_xSr_{1-x})Ti_{1+y}O_{3+z}$ Thin Films Grown By Chemical Vapor Deposition** .... Susanne Stemmer
9:40	**O4, A Mass Spectral Study of the Surface Decomposition Chemistry of Precursors for Chemical Beam Epitaxy of Lithium Niobate** .... Dovas Saulys
10:00	**Break**
10:20	**O5*, Advanced Gate Dielectrics for Scaled CMOS** .... Glen Wilk
11:00	**O6, Characterization of MFIS and MFMIS Structures Using SrBi2Ta2O9 Film with SrTa2O6/SiON Stacked Buffer Layer** .... Eisuke Tokumitsu
11:20	**O7, Process Integration of TEOS-Based SiO2 Films for Inter-Layer Dielectric on Ferroelectric Capacitors** .... Yanghan Yoon
11:40	**O8, Photo-Patternable Precursors to Oxide Electrodes for Ferroelectric Memory Devices** .... Charles D. E. Lakeman

Session P. Ordering in Semiconductor Alloys

Room: Corwin East

1:30	**P1,** Ordered InGaAs: Low-Temperature MOVPE Growth and Polarization Dependent Electroabsorption Measurements .... Werner Prost
1:50	**P2,** Microstructure of CuPt-B Ordered GaInAs Films .... S.P. Ahrenkiel
2:10	**P3,** Phase Separation and Ordering Co-Existing in MOCVD $In_xGa_{1-x}N$ .... Mark K Behbehani[1]
2:30	**P4,** Band Structure and Stability of Ordered Zinc-Blende-Based Semiconductor Polytypes .... Su-Huai Wei
2:50	**P5,** X-Ray Diffraction Study of Ordering in Epitaxial ZnSnP .... Sebastien Francoeur
3:10	**Break**
3:30	**P6,** Comparison of Dopants used to Control Ordering in GaInP .... Chris Fetzer
3:50	**P7,** Ordering and Antiphase Boundaries in Te-doped GaInP Layers Grown by Organometallic Vapour Phase Epitaxy .... T-Y Seong
4:10	**P8,** Maximum Direct-Gap Reduction in CuPt Ordered $Al_xGa_{1-x}InP$ (0 £ x £ 1) Determined by Generalized Ellipsometry .... M. Schubert
4:30	**P9+,** Observation of Type I/II Transition in GaAs/InGaP Heterostructure by C-V Profiling .... Shouvik Datta
4:50	**P10,** Late News

Session Q. Nanostructure Self-Assembly

Room: Corwin West

1:30	**Q1,** In-Situ Growth of InAs Quantum Dots on Patterned GaInAs/InP Nanostructures .... Werner Seifert
1:50	**Q2,** Formation of Nanoscale Self-Assembled $Si_{1-x}Ge_x$ Islands Using Chemical Vapor Deposition and Subsequent Thermal Annealing of Thin Metastable Films .... Rashid Bashir
2:10	**Q3+,** Fabrication and Characterization of Magnetic Semiconductors "Spin Wires" and "Spin Dots" .... O Ray
2:30	**Q4,** Preparation and Characterization of Gold-Platinum Nanorods .... Theresa Mayer
2:50	**Q5+,** Self-Assembly of Patterned Films of Nanometer-Diameter Gold Clusters that are Linked by Organic Molecules .... Jia Liu
3:10	**Break**
3:30	**Q6+,** Directed Self-Assembly of Metal/Semiconductor Structures for Nanoelectronic Devices and Circuits .... Brian L. Walsh
3:50	**Q7,** Dry-Etched Grating in the MQW Active Layer for DFB Laser Arrays Fabrication .... Taheau Anne
4:10	**Q8,** Various AFM Nano-Oxidation Processes for Planar Type Single Electron Transistor .... K.Matsumoto
4:30	**Q9+,** Semiconductor Patterning Techniques Based on Self-Assembled Structures .... M.V. Batistuta
4:50	**Q10,** Thermo-Mechanical Properties of Polymers for Nanoimprint Lithography .... Thomas Hofmann

Session R. Properties of InGaN Heterostructures and Devices

Room: Lotte Lehman Hall

1:30	**R1,** Single-Mode Nitride-Based Laser Diodes Using Thick n-AlGaN Layers .... T. Takeuchi
1:50	**R2,** Violet-Blue InGaN/GaN MQW Light Emitting Diodes on Epitaxially Laterally Overgrown GaN .... Koen Jacobs
2:10	**R3,** Dislocation Reduction in GaN Epilayers via Lateral Overgrowth from Trenches .... Y. Chen
2:30	**R4+,** Measurement of Crystallographic Tilt in the Lateral Epitaxial Over growth of GaN .... Paul T. Fini
2:50	**R5+,** MOCVD Growth and Characterization of AlInGaN Quaternary Alloys .... Michael E. Aumer
3:10	**Break**
3:30	**R6,** Behavior of Quantum Well Excitons, under Internal Fields of GaN/AlGaN and InGaN/GaN/AlGaN Quantum Well Structures .... Shigefusa F. Chichibu
3:50	**R7,** Piezoelectric Effects in the Radiative Centers of GaInN/GaN Quantum Wells and Devices .... Christian Wetzel
4:10	**R8,** Phase Separation in InGaN/GaN MQWs: .... L. T. Romano
4:30	**R9+,** Role of Below Bandgap States in the Radiative Emission of InGaN/GaN Quantum Well Structures: .... Georgiy O. Vaschenko
4:50	**R10+,** Optical Band Gap Dependence on Thickness and Composition of InGaN Grown on GaN .... Christopher Arlen Parker

Session S. Silicon Carbide Processing for Devices

Room: Multicultural Center Theater

1:30	**S1,** Phosphorus and Nitrogen Implantation into 4H-SiC .... Michael A. Capano
1:50	**S2,** Hydrogen Passivation of Aluminum and Boron Acceptors in SiC by Low Energy Ion Implantation .... Norbert Achtziger
2:10	**S3+,** Effect of Implant Activation Annealing Conditions on the Inversion Channel Mobility in 4H- and 6H-SiC MOSFETs .... Mrinal Kanti Das
2:30	**S4,** Electrical Characteristics of Schottky Barriers on 4H-SiC: The Effects of Barrier Height Nonuniformity .... B. J. Skromme
2:50	**S5+,** Characteristics of Nickel Schottky Junctions on Trench Sidewalls of Reactive Ion Etched 4H-SiC Surfaces .... V. Khemka
3:10	**Break**
3:30	**S6,** High Rate Etching of Silicon Carbide .... F. Khan
3:50	**S7,** Fast, Smooth, and Anisotropic Etching of SiC using SF6/Ar .... Myeong S. So
4:10	**S8,** Analysis of the Temperature Dependence of the the SiO_2/SiC Barrier Height .... Richard Waters
4:30	**S9,** Atomic-Scale Mechanisms of Oxygen Precipitation and Thin-Film Oxidation of SiC .... Massimiliano Di Ventra
4:50	**S10,** Late News

Session T. Materials Integration: Growth and Characterization

Room: State Street Room

1:30	**T1,** Lattice-Mismatched InGaAs Layers Grown on GaAs and InP Compliant Substrates .... Koen Vanhollebeke
1:50	**T2,** A Comparison of Experimental and Calculated HRXD Spectra of Mismatched InGaAs Films Grown on Borosilicate Glass-Bonded GaAs Compliant Substrate Structures .... P. D. Moran
2:10	**T3+,** Strain Relaxation in $In_xGa_{1-x}As$ Lattice Engineered Substrates .... Prashant M. Chavarkar
2:30	**T4+,** On the Strain Relaxation and Misfit Dislocation Introduction Mechanisms in Highly Lattice Mismatched InAs/GaP Epitaxy .... Vidyut Gopal
2:50	**T5,** Epitaxial Growth and UV Luminescence of CaF2/ZnO/CaF2 Heterostructures on Si(111) .... Masahiro Watanabe
3:10	**Break**
3:30	**T6,** Comparison of InGaSb/InAs Superlattice Structures Grown by MBE on GaSb, GaAs, and Compliant GaAs Substrates .... D. H. Tomich
3:50	**T7,** Low Dislocation Relaxed SiGe Grown on a Novel Compliant Substrate .... Yuhao Luo
4:10	**T8,** Optically-Pumped Mid-Infrared Lasers on Traditional and Compliant Substrates .... Stefan J. Murry
4:30	**T9,** Optically Pumped Stimulated Emission in Freestanding GaN Prepared by Hydride Vapor Phase Epitaxy .... S. T. Kim
4:50	**T10,** Late News

Session U. Thermophotovoltaic Materials & Devices

Room: Santa Barbara Harbor Room

1:30	**U1,** Photon Recycling in 0.53 eV InGaAsSb .... Greg Walter Charache
1:50	**U2,** Spectral Ellipsometry of GaSb and GaInAsSb/GaSb: Experiment and Modelling .... Martin Munoz
2:10	**U3,** Phase Instabilities and Micro-structure in InGaAsSb/GaSb Heterostructures .... Krishna Rajan
2:30	**U4,** OMVPE Growth of InGaAsSb Thermophotovoltaic Cells .... Z. A. Shellenbarger
2:50	**U5,** A Study of the Relative Tilt of GaInSb Epitaxial Layers on GaSb Substrates Grown by Metalorganic Vapor Phase Epitaxy .... Ishwara B. Bhat
3:10	**Break**

Thursday Afternoon (Cont'd)

Session V. Thermoelectric and Other Narrow Gap Materials

Room: Santa Barbara Harbor 1

3:30 **V1, MOCVD Growth of High Mobility InSb on Si Substrates for Hall Effect Applications**
.... Michael W. Pelczynski

3:50 **V2, The Effect of Annealing Temperature on the Structural and Electrical Properties of Au/n-GaSb Contacts**
.... H. Ehsani

4:10 **V3, 300K Thermoelectric Figure of Merit in the Range of 3 Utilizing Phonon Blocking Electron-Transmitting Structures**
_____Rama Venkatasubramanian

4:30 **V4, Thermoelectric Quantum Dot Superlattices**
.... T.C. Harman

4:50 **V5, Temperature Dependence of Thermionic Emission Cooling in Single Barrier and Superlattice Heterostructures**
.... Ali Shakouri

Session W. Epitaxy of III-V

Room: Corwin East

8:20 **W1+, Structural and Optical Properties of Strained InGaAs/GaAs Quantum Wells Grown by MOVPE on (111)A GaAs Substrates**
.... Soohaeng Cho

8:40 **W2+, An Investigation on the Mechanisms Responsible for Ar+-Laser Induced Growth Enhancement Of GaAs by Chemical Beam Epitaxy**
.... Bin Q. Shi

9:00 **W3, Enhancement of Electron Mobilities in Pseudomorphic $In_{0.7}Ga_{0.3}As/In_{0.52}Al_{0.48}As$ Modulation-doped Quantum Wells with (411)A Super-flat Interfaces Grown by Molecular Beam Epitaxy**
.... Takahiro Kitada

9:20 **W4, High Quality GaAs0.68P0.32/In0.13Ga0.87P/Si QW Structure with a Very Few Threading Dislocations**
.... Yasuhiro Fujimoto

9:40 **W5+, Dependence of Cracker Temperature to Silicon Doing Concentration in InGaAlP Layers Grown by Solid Source Molecular Beam Epitaxy**
.... Yi-Cheng Cheng

10:00 **Break**

Session X. Composite Materials and Applications

Room: Corwin East 1

10:20 **X1+, Transit Time and Light Absorption Effects in ITG-GaAs and Applications to MSM-Photodetectors**
.... Vijay Krishnamurthy

10:40 **X2+, Ultrafast Carrier Dynamics in Be-doped Low Temperature Grown GaAs Studied by Double-Pulse Excitation**
.... Ri-an Zhao

11:00 **X3+, Experimentally Verified Conduction Model for a Low-Resistance Non-Alloyed Ohmic Contact Utilizing Low-Temperature-Grown GaAs**
.... N.-P Chen

11:20 **X4+, Thermal Conductivity of Low-Temperature-Grown GaAs**
.... Andrew W. Jackson

11:40 **X5, Surface Atomic Process of Incorporation of Excess Arsenic in Molecular Beam Epitaxy of GaAs**
.... N. Otsuka

Session Y. Properties of Quantum Wires and Wells

Room: Corwin West

8:20   **Y1, Structural and Alloy Composition Uniformity of InGaAs Ridge Quantum Wires Grown by Selective MBE on Patterned InP Substrates** .... Chao Jiang

8:40   **Y2, Spin Splitting of Exciton Band in Asymmetric Double Quantum Wells** .... Guangyou Yu

9:00   **Y3, Mobility Edge and Exciton Relaxation in CdSe/ZnSe Quantum Wells** .... Jinxi Shen

9:20   **Y4, Recombination Lifetime Measurements of InGaN/GaN Multiple Quantum Wells** .... Eunjoo Shin

9:40   **Y5, Study of Temperature-Dependent Photocurrent and Dark Current Measurements for a Maximization of Carrier Collection and a Voltage Enhancement of MQW p-i-n Diodes** .... Cedric Monier

10:00   **Break**

10:20   **Y6, Improved Heterointerface Quality of AlGaAs/GaAs Quantum Wires Characterized by AFM and Microscopic Optical Measurements** .... Xue-Lun Wang

10:40   **Y7+, Optical Properties in InGaN/GaN Structures Grown by Metal-Organic Chemical Vapor Deposition** .... Mee Yi Ryu

11:00   **Y8, Modulation Spectroscopy Study of a Strained Layer GaAs/GaAsP Multiple Quantum Well Structure** .... L. Malikova

11:20   **Y9, The Annealing Effects on Optical and Structural Properties of (ZnSe)2(CdSe)n Short-Period Superlattices Multiple Quantum Wells** .... Ru Chin Tu

11:40   **Y10+, Transient Luminescence and Exciton Dynamics in (CdMn)Te(CdMg)Te Quantum Wells** .... Mukul C. Debnath

Session Z. Wide Bandgap Nitrides (MBE, Theory, and AlN)

Room: Lotte Lehman Hall

8:20   **Z1+, Dielectric and Lattice-Dynamical Properties of III-Nitrides (Student Paper)** .... Ulrike Grossner

8:40   **Z2, Pressure Coefficient of Nitrides and Their III-V Alloys** .... Su-Huai Wei

9:00   **Z3, Measurement of Al Mole Fraction of Bulk AlGaN and AlGaN/GaN Heterostructures by Photoconductance and Reflectance Methods** .... L. S. Yu

9:20   **Z4+, Growth of Bulk AlN by Physical Vapor Transport** .... Tim Housain

9:40   **Z5, Microstructural Analysis of the Recrystallization in AlN Nucleation Layers** .... Yves-Matthieu Le Vaillant

10:00   **Break**

10:20   **Z6, Lateral Epitaxial Overgrowth of GaN films by Molecular Beam Epitaxy** .... M. R. Hoit

10:40   **Z7, Strain Relaxation and Homogeneity of AlGaN Grown by Molecular Beam Epitaxy** .... Sven Einfeldt

11:00   **Z8+, Surfactant Effect and Polarity Inversion Due to Mg on the GaN(0001) Surface** .... V. Ramachandran

11:20   **Z9, Influence of Structural Defects on Transport Properties of GaN Grown by Reactive MBE and Magnetron Sputter Epitaxy (MSE)** .... Haipeng Tang

11:40   **Z10+, Optimization of High Quality GaN by MBE** .... B. Heying

Session AA. Metal Contacts to Wide Band Gap Semiconductors

Room: Multicultural Center Theater

8:20   **AA1, Large Schottky Barriers and Memory Operation for Ni/p-GaN Contacts** .... Kenji Shiojima

8:40   **AA2+, High Temperature Behavior of Barrier Height and Ideality Factor of Ni/Au Contacts to p-type GaN** .... Ricky Wenkuei Chuang

9:00   **AA3, Current Transport Mechanism of Low-Resistance TaTi Ohmic Contact Materials for p-GaN** .... Yasuo Koide

9:20   **AA4+, Indium Tin Oxide as a Transparent Contact to p-GaN** .... Oded Buchinsky

9:40   **AA5+, Surface Treatment of p-GaN by KOH Solution Studied by Synchrotron Radiation Core-Level Spectroscopy** .... Jingxi Sun

10:00   **Break**

10:20   **AA5+, Characterization of Rhenium Schottky Contacts on n-Type AlxGa1-xN at High Temperatures** .... L. Zhou

10:40   **AA6, Improved Surface Morphology and Thermal Stability of Al/Ti/n-GaN** .... Joon Seop Kwak

11:00   **AA7+, A New Approach to Thermodynamically Stable Contacts for Binary Wide Bandgap Semiconductors** .... Ilan Shalish

11:20   **AA8, Metallization Schemes for High Temperature Electrical Contacts to Silicon Carbide** .... Lisa M. Porter

11:40   **AA9, Effect of Si1-xCx Interface Layer on the Properties of Metal Contacts to p-type SiC** .... Johnson Olufemi Olowolafe

1999 EMC At-A-Glance
Friday Morning, July 2, 1999

Session BB. Etching and Passivation of Compound Semiconductors
Room: State Street Room

8:20 **BB1+, In Situ Etch and Regrowth of a InAs/AlGaSb Heterostructure** .... Giovanni Bellomi

8:40 **BB2+, Inductively Coupled Plasma Selective Reactive Ion Etching of GaAs/InGaP For Device Fabrication** .... W. Lanford

9:00 **BB3, GaAs/AlGaAs Selective Dry Etching by Sawtooth-wave Modulated Inductively Coupled SiCl4/SF6 Plasma** .... Yusuke Matsukura

9:20 **BB4, Air-Stable Surface Passivation of III-V Semiconductors and Application to Devices** .... Carol I. H. Ashby

9:40 **BB5, Effects of Chemical Treatments and Sulfide Passivation on Surface Recombination in GaN** .... G. L. Martinez

10:00 **Break**

10:20 **BB6, Investigation of the Chemisorption and Reaction of Chlorine with the GaN (0001) Surface** .... Jingxi Sun

10:40 **BB7, Photoluminescence Measurements of Dry Etch Damage in GaN** .... Elaine D. Haberer

11:00 **BB8, A Simple Wet Etch for GaN** .... Jennifer A. Bardwell

11:20 **BB9, Photoelectrochemical Etching of GaN for Materials Characterization and Device Fabrication** .... I. Adesida

11:40 **BB10+, Development of Photoelectrochemical Etching for Gallium Nitride Device Fabrication** .... A. R. Stonas

Session CC. Defects and Defect Engineering for Devices
Room: Santa Barbara Harbor Room

8:20 **CC1+, Wafer Edge Misfit Dislocation Nucleation in p/p+ Vapor Phase Silicon** .... Petra Feichtinger

8:40 **CC2, Reduction of Defect Induced Leakage Currents by the Use of Nitrided Field Oxides in Selective Epitaxial Growth (SEG) Isolation for Silicon ULSI** .... Rashid Bashir

9:00 **CC3+, Selective SiGe Nanostructures Grown by UHVCVD** .... Thomas Andrew Langdo

9:20 **CC4+, Minority Carrier Properties and Defects in MBE-Grown AlGaAs/ GaAs Heterostructures on Ge** .... John A. Carlin

9:40 **CC5+, Performance and Microstructure of Visible Light-Emitting Diodes Grown on High-Quality InGaP/GaP Epitaxial Transparent Substrates by MOVPE** .... Andrew Y. Kim

10:00 **Break**

10:20 **CC6, Photoreflectance Study of Passivation of GaAs** .... Richard Beaudry

10:40 **CC7, Reversal of Electrical Stress Degradation in Fully Self-Aligned InP/GaAsSb/InP DHBTs by a Surface Treatment in Ozone** .... Colombo R. Bolognesi

11:00 **CC8+, Traps in Pseudomorphic InGaAs/AlGaAs/GaAs HEMTs Measured by Deep Level Capacitance and Current Transient Spectroscopy** .... Evelyn N. Wang

11:20 **CC9+, Physical Evidence of Hydrogen Degradation of InP HEMTs** .... Roxann R. Blanchard

11:40 **CC10, Late News**

Session DD. Non-Destructive Testing and "In-Situ" Monitoring/Control
Room: Corwin East

1:30 **DD1, Characterization of p-Dopant Interdiffusion in 1.3 μm InGaAsP/InP Laser Structures Using Modulation Spectroscopy** .... A. Jeager

1:50 **DD2, Room Temperature Polarized Photoreflectance Hotoreflectance Characterization of GaAlAs/InGaAs High Electron Mobility Transistor Structures Including the Influence of Strain Relaxation** .... Yingsheng Huang

2:10 **DD3+, Depth Defined Optoelectronic Modulation Spectroscopy** .... John Garth Swanson

2:30 **DD4+, Surface Photovoltage Spectroscopy of Two Dimensional Structures and Devices** .... Nurit Ashkenasy

2:50 **DD5+, UHV Contactless Capacitance-Voltage Characterization of Free Silicon Surfaces** .... Toshiyuki Yoshida

3:10 **Break**

3:30 **DD6+, Far UV Spectroscopic Reflectometry** .... S. Lim

3:50 **DD7, Spectroscopic Ellipsometry for Real-Time Control of Heteroepitaxy of HgCdTe on Si** .... L. A. Almeida

4:10 **DD8, In Situ Controlled Electronic Properties of Low Temperature GaAs (001) for Two-Photon Absorbes** .... J. Herfort

4:30 **DD9+, Investigation of Indium Surface Segregation in Solid Source MBE Growth of InxGa1-xSb** .... David H. Tomich

4:50 **DD10, Improved Composition and Layer Interface Control by Modeling Knudsen Cell Heating Cycle** .... Stephen. J. Adams

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1999 EMC At-A-Glance
Friday Afternoon, July 2, 1999

Session EE. Semiconductor Quantum Dots - Electronic Structures

Room: Corwin West

1:30 EE1, Modified Fermi-Level Pinning of the (100) GaAs Surface Through InAS Quantum Dots in Different Stages of Overgrowth .... Carsten Walther

1:50 EE2, Tunneling Spectroscopy of Electron States in Self-Assembled InAs Dots .... Kanji Yoh

2:10 EE3, Variation of the Potential Well of Self-assembled InAs/GaAs Quantum Dots with Fixed Ground State Luminescence Energy .... Markus Arzberger

2:30 EE4, Electrical Detection of Optically Induced Charge Storage in Self Assembled InAs Quantum Dots .... Doris Heinrich

2:50 EE5, Dark Excitons Due to Direct Coulomb Interactions in Silicon Quantum Dots .... Fernando A. Reboredo

3:10 Break

3:30 EE6, Photoluminescence of Strain-Induced Coupled Quantum Dot-Pairs .... H.-W. Ren

3:50 EE7, Experimental Determination of Intra-level Relaxation Time in Quantum Dots with Different Energy Level Spacing .... H. Koskenvaara

4:10 EE8, Band Structure Modification of InP Dots at High Pressure .... Linshi Miao

Session FF. Issues of Dopants and Defects in Nitrides

Room: Lotte Lehman Hall

1:30 FF1+, Influence of Dislocations in InGaN/GaN Quantum Well Grown by Metalorgaic Chemical Vapor Deposition .... Tomoya Sugahara

1:50 FF2, Atomic Scale Analysis of Defect Structures and Properties in III-nitride Materials by Z-Contrast Imaging and EELS in STEM .... Yan Xin

2:10 FF3, Investigation of the Formation of the 2.8 eV PL Band in p-type GaN .... Fatemeh Shahedipour

2:30 FF4, Effect of Threading Dislocations, Mg-Doping and Etching on the Photoconductivity Spectra of GaN .... John T. Torvik

2:50 FF5, Optically Detected Magnetic Resonance Study of Defects in Undoped, Be-doped, and Mg-doped GaN .... Friedrich Karl Koschnick

3:10 Break

3:30 FF6, Optical Properties of Rare Earth Doped GaN Grown by MBE .... Andrew J. Steckl

3:50 FF7, Near-Surface Cathodoluminescence Spectroscopy of Erbium Doped AlN Alexander P. Young

4:10 FF8, Isoelectronic Doping of Gallium Nitride with Arsenic .... Peter H. Mitev

4:30 FF9, Yellow Luminescence and Electrical Conductivity in GaN .... Ilan Shalish

4:50 FF10, Electric Force Microscopy of Induced Charges and Surface Potentials in GaN Modified by Light and Strain .... P. M. Bridger

Session GG. Epitaxy of II-VI and Chalcopyrites

Room: State Street Room

1:30 GG1, Homoepitaxy of ZnTe by MBE .... J. H. Chang

1:50 GG2, High Quality ZnSe layers with an Atomically Flat Surface Grown on GaAs(001) by Molecular Beam Epitaxy .... Kenat Arai

2:10 GG3, Growth and Characterization of Multiple Quantum Wells of $ZnSn(P_xAs_{1-x})$/GaAs .... Georgiy A. Seryogin

2:30 GG4, Epitaxial Growth of g-In_2Se_3 Films with a Defect Wurtzite Structure by Molecular Beam Epitaxy .... Tomohiko Ohtsuka

2:50 GG5, Late News

3:10 Break

Session HH. Epitaxy of Si, III-V, Oxides

Room: Santa Barbara Harbor Room

1:30 HH1, Characterization of Silicon Atomic-Layer-Epitaxy by an Atomic-Force Microscope .... Keiji Ikeda

1:50 HH2, Surface Phases of InP (001) in the MOVPE Process .... Robert F. Hicks

2:10 HH3, The Structure of Aluminum Antimonide Surfaces Grown by Molecular Beam Epitaxy .... Allan S. Bracker

2:30 HH4, MBE Growth of ZnO Films on GaN and Characterization .... H. J. Ko

2:50 HH5, Plasma Assisted Molecular Beam Epitaxy and Characterization of the MgxZn1-xO.ZnO Hetero-Structures .... Yefan Chen

3:10 Break

1999 Electronics Materials Conference Grid

	WEDNESDAY AM	WEDNESDAY PM	THURSDAY AM	THURSDAY PM	FRIDAY AM	FRIDAY PM
Multicultural Lounge	REGISTRATION 7:30AM-5:00PM		REGISTRATION 7:30AM-4:00PM		REGISTRATION 7:30AM-10:00AM	
Lagoon Plaza	EXHIBIT 10:00AM-5:00PM Coffee Breaks AM-PM RECEPTION 7:00PM-9:00PM		EXHIBIT 10:00AM-4:00PM Coffee Breaks AM-PM		Coffee Break AM	
Corwin Pavilion	EMC Plenary Lecture/Student Awards					
Corwin East			Session J. Epitaxy for Devices	Session P. Ordering in Semiconductor Alloys	Session W. Epitaxy of III-V / Session X. Composite Materials and Applications	Session DD. Non-Destructive Testing and "In-Situ" Monitoring/ Control
Corwin West			Session K. Nanoscale Characterization	Session Q. Nanostructure Self-Assembly	Session Y. Properties of Quantum Wires and Wells	Session EE. Semiconductor Quantum Dots-Electronic Structures
Lotte Lehman Hall {Music Bldg.}		Session E. Special Topical Session	Session L. Wide Bandgap AlGaN/GaN Heterostructures	Session R. Properties of InGaN Heterostructures and Devices	Session Z. Wide Bandgap Nitrides (MBE, Theory, and AIN)	Session FF. Issues of Dopants and Defects in Nitrides
Multicultural Ctr Theatre	Session A. Semiconductor Quantum Dots-Devices	Session F. Semiconductor Quantum Dots-Formation and Structure	Session M. SiC Growth & Characterization	Session S. Silicon Carbide Processing for Devices	Session AA. Metal Contacts to Wide Band Gap Semiconductors	
State Street	Session B. Materials Integration-Substrate Fabrication & Bonding	Session G. Epitaxy for Devices	Session N. Infrared Materials and Devices	Session T. Materials Integration: Growth and Characterization	Session BB. Etching and Passivation of Compound Semiconductors	Session GG. Epitaxy of II-VI and Chalcopyrites
Santa Barbara Harbor	Session C. Characterization, Growth and Properties of Organic Electronic Materials	Session H. Electronic Transport in Organic & Molecular Materials	Session O. Issues for Ferroelectric and High Permittivity Thin Film Materials	Session U. Thermophotovoltaic Materials & Devices / Session V. Thermoelectric & Other Narrow Gap Materials	Session CC. Defects and Defect Engineering for Devices	Session HH. Epitaxy of Si, III-V, Oxides
Flying A Studios	Session D. Oxides for Devices	Session I. Column IV Heterostructures and Devices				

1999 Electronic Materials Conference
TECHNICAL PROGRAM

University of California·Santa Barbara, California · June 30 - July 2, 1999

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* Indicates Invited Paper   **+ Indicates Student Paper**

EMC PLENARY LECTURE/ STUDENT AWARDS

Wednesday AM   Room: Corwin Pavalion
June 30, 1999   Location: University Center

Session Chair: Thomas Kuech, University of Wisconsin, Department of Chemical Engineering, Madison, WI 53706

Ceremony: 8:30 AM

Plenary Speaker: *Shuji Nakamura,* Nichia Chemical Industries, Ltd., R&D Dept., 491, Oka, Kaminaka, Anan, Tokushima Japan

Topic: "Present and Future Prospects of InGaN-Based Blue LEDs and LDs"

Highly efficient light-emitting diodes (LEDs) emitting ultraviolet (UV), blue, green, amber and red light have been obtained through the use of InGaN active layers instead of GaN active layers. Red LEDs with an emission wavelength of 675 nm, whose emission energy was almost equal to the band-gap energy of InN, were fabricated. The dependence of the emission wavelength of the red LED on the current (blueshift) is dominated by both the band-filling effect of the localized energy states and the screening effect of the piezoelectric field. In the red LEDs, a phase separation of the InGaN layer was clearly observed in the emission spectra, in which blue and red emission peaks appeared. In terms of the temperature dependence of the LEDs, InGaN LEDs are superior to the conventional red and amber LEDs due to a large band offset between the active and cladding layers. The localized energy states caused by In composition fluctuation in the InGaN active layer contribute to the high efficiency of the InGaN-based emitting devices, in spite of the large number of threading dislocations and a large effect of the piezoelectric field. The blue and green InGaN-based LEDs had the highest external quantum efficiencies of 18% and 17% at low currents of 0.6 mA and 0.1 mA. The luminous efficiency (60 lm/W) of green LEDs is close to that of a fluorescent light (80 lm/W). Thus, there is a possibility of replacing conventional incandescent bulbs and fluorescent lights with LED all-solid-state light sources in the near future. An violet InGaN multi-quantum-well (MQW)/GaN/AlGaN separate-confinement-heterostructure laser diode (LD) with an emission wavelength of 400 nm was grown on epitaxially laterally overgrown GaN on sapphire. The threshold current density was 2-4 kA/cm2. The LDs with cleaved mirror facets showed an output power as high as 30 mW under room-temperature continuous-wave (CW) operation. The stable fundamental transverse mode in the near-field patterns was observed at an output power up to 30 mW. The lifetime of the LDs at a constant output power of 5-30 mW was more than 1,000 hours under CW operation at an ambient temperature of 50°C. The estimated lifetime was approximately 3,000 hours under these high power and high temperature operating conditions. These results indicate that these LDs already can be used for many real applications, such as DVDs, laser printers, sensors and exciting light sources as a commercial product with a high output power and a high reliability.

BREAK: 9:30 AM - 10:00 AM

Session A. Semiconductor Quantum Dots - Devices

Wednesday AM   Room: Multicultural Center Theater
June 30, 1999   Location: University Center

Session Chairs: Kang Wang, University of California, Los Angeles, CA USA; Mark Miller, University of Virginia, Dept. of Elect. Eng., Charlottesville, VA USA

10:00 AM
Gain and Emission Characteristics of MOVPE Grown InP/GaInP Quantum Dot Lasers: *Thomas Riedl*[1]; Joerg Porsche[1]; Markus Ost[1]; Ferdinand Scholz[1]; Andreas Hangleiter[1]; [1]University of Stuttgart, 4th Physical Institute, Pfaffenwaldring 57, Stuttgart 70550 Germany

The optical properties of self-assembled quantum dots (QDs) grown in the Stranski-Krastanow growth mode have attracted a lot of interest over the past few years both due to their fundamental physics and potential device application. A lot of investigations have been performed in the material system InGaAs/GaAs and some results concerning QD injections lasers are quite promising. In the material system InP/GaInP, however, which gives a pathway to QD lasers emitting in the visible part of the spectrum, knowledge about the QD electronic structure, gain of the excited states and the consequences for lasers is limited. Laser structures with a single layer of self organized InP/GaInP QDs grown by metalorganic vapour-phase epitaxy (MOVPE) have been investigated by power-dependent photoluminescence (PL), photoluminescence excitation (PLE) and optical gain measurements. The consequences of our findings are directly compared to the emission characteristics of MOCVD grown InP/GaInP QD injection lasers that we fabricated for the first time. The samples were grown on (100) GaAs substrate tilted towards the (111)B plane by 15° in order to suppress a bimodal size distribution of the dots an to preferentially obtain smaller dots. At low excitation densities we observe strong PL due to the QD ground state at 1.7-1.72 eV (5K) with a FWHM of 30 meV due to nonuniformities in size and shape. Increasing the excitation density saturates the QD ground state and pronounced excited states become visible. Absorption due to these excited states is clearly found in PLE measurements and shows an excellent agreement with the PL results. We also performed optical gain measurements on the laser structures using the variable stripe length method. Gain due to the dots is found in transverse electric (TE) polarization, while there is no gain in transverse magnetic (TM) polarization. At high excitation densities our samples also show gain due to the GaInP waveguide which does not depend on polarization. The excited state features found in PL and PLE are also visible in our gain measurements. However the excited states show comparable and even higher modal gain than the ground state even before the ground state is completely saturated. Our single layer injection lasers behave as expected from our above findings. Above threshold (about 500 A/cm2) they emit strongly TE polarized at 1.78-1.82 eV (90K) which can be clearly identified as lasing due to an excited state of the QDs. This leads to a rather weak carrier confinement (wetting layer \@ 1.88 eV) and poor temperature characteristics. Thus it is necessary to either reduce internal as well as mirror losses or

use lasers with QD stacks to obtain groundstate lasing and by this means a better performance of our lasers.

10:20 AM

4 Watt High Power Quantum Dot Lasers: *M. Grundmann*[1]; Ch. Ribbat[1]; M.-H. Mao[1]; F. Heinrichsdorff[1]; N. N. Ledentsov[1]; D. Bimberg[1]; A. R. Kovsh[2]; A. Yu. Egorov[2]; D. A. Lifshits[2]; M. V. Maximov[2]; Yu. M. Shernyakov[2]; V. M. Ustinov[2]; A. E. Zhukov[2]; Zh. I. Alferov[2]; [1]TU Berlin, Institute of Solid State Physics, PN 5-2, Hardenbergstr. 36, Berlin 10623 Germany; [2]A.F. Ioffe Physico-Technical Institute, Polytechnicheskaya 26, St. Petersburg 194021 Russia

The use of quantum dots (QDs) offers, via zero-dimensional charge carrier localization and reduction of charge carrier diffusion, potential advantages for high power lasers. Reduced non-radiative surface recombination decreases facet overheating and higher COD threshold is expected. Those advantages can be combined with the low threshold, the high temperature stability and the extended wavelength range of QD lasers to create high power lasers with lower temperature sensitivity, slightly larger wall-plug efficiency than conventional quantum well-based lasers. No real high power devices, however, were reported yet. We have fabricated high power QD lasers using MOCVD (TUB) and MBE (Ioffe). The MOCVD lasers are based on three-fold and six-fold stacks of InGaAs/GaAs QDs in Al-free GaAs/GaInP waveguides. An emission wavelength around 1100 nm is intended for the pumping of fiber (up-conversion) lasers for the blue spectral range which is currently not commercially available. The wafers have been processed into ridge waveguide Fabry-Perot devices with injection stripe width of 50 μm. For a cavity length of 1mm they exhibit an output power of 12 mW (l=1068 nm) during pulsed operation (650 ns pulses, 1/384 duty cycle) at room-temperature, corresponding to 4.5 W cw operation. The slope efficiency is 0.72W/A. We find a rather small vertical far field divergence ($1/e^2$) of 31°; the lateral divergence is 4.5°. The spectral characteristics under injection indicate a non-thermal (i.e. not Fermi) carrier distribution. The MBE grown lasers contain a triple stack of InAlAs/AlGaAs seed layer dots and a triple stack of (the laser active) InAs/AlGaAs QDs. The optical cavity was 0.4 μm thick. The devices have been operated continuously at room-temperature and exhibited a maximum optical output power of 3.6 W (at 840 nm) at 10°C heat sink temperature. The stripe width was 100 μm and the cavity length 945 μm. The differential efficiency was 80% (1.12 W/A) in a cw mode. The internal quantum efficiency was determined to be 92%.

10:40 AM

Electroluminescence of Stacked In(Ga)As/GaAs QDs at 1.3 mm - 1.4 mm: *Frank Heinrichsdorff*[1]; Nikolai Zakharov[2]; Peter Werner[2]; Alois Krost[1]; Dieter Bimberg[1]; [1]Technische Universität Berlin, Institut für Festkörperphysik, Sekr. PN 5-2, Berlin 10623 Germany; [2]Max-Planck-Institut für Mikrostrukturphysik, Weinberg 6, Halle, 06120 Germany

The realization of light emitters for the 1.3 mm spectral range on GaAs substrates is a challenging task, since such devices - which cannot be produced with "classical" InGaAs/GaAs quantum wells - could serve as a cheaper replacement for InP-based lasers and LEDs. Furthermore, the possibilities for the integration of 1.3 mm light emitters with GaAs-based electronics and the fabrication of (monolithic) 1.3 mm VCSELs with AlGaAs/GaAs Bragg mirrors are of great promise /1/. We describe the MOCVD growth and characterization of 1.3-1.4 mm electroluminescence InGaAs/GaAs quantum dot devices. The AsH_3 pressure turns out to be the key parameter to determine the size and emission wavelength of the QDs via modification of the adatom mobility during growth. To overcome the problems of defect formation and low QD density during the growth of large QDs under high adatom mobility conditions, we use the concept of QD seeding to predefine the nucleation sites for the large QDs /2,3/. The combination of one or two layers of small QDs ("seed" layers, @12 nm base width) and a single sheet of large QDs (@18 nm base width) separated by 2-5 nm of GaAs leads to vertically correlated QD growth with low defect density, as directly proven by TEM and AFM investigations. Depending on the separation layer thickness and amount of material deposited, lateral QD densities of up 6×10^{10} cm^{-2} and a maximum emission wavelength of 1.42 mm have been achieved. Surprisingly, the dislocation density is found to be strongly dependent on the cap layer growth rate. TEM and PL measurements consistently show that the lowest dislocation densities are observed when the GaAs cap layer is grown at very low growth rates (r_G= 120 nm/h) or in migration enhanced mode. However, under these conditions the QD luminescence is blue shifted by 40 - 50 nm as compared to samples where the cap layer has been grown at three times higher growth rates. This impact of the cap layer growth rate is explained by enhanced In-redistribution during slow cap layer growth. First room-temperature electroluminescence spectra indicate the onset of ground state saturation at ~100 A/cm^2 and continuous state filling for a further increase of the current density. /1/ D. Bimberg, M. Grundmann and N.N. Ledentsov, "Quantum Dot heterostructures", John Wiley & Sons, Chichester, 1998 /2/ I. Mukhametzhanov, R. Heitz, J. Zeng, P. Chen and A. Madhukar, Appl.Phys.Lett. 73, 1841 (1998) /3/ M.V. Maximov, D.A. Bedarev, A.Yu. Egorov, P. S. Kop'ev, A. R. Kovsh, A.V. Lunev, Yu.G. Musikhin, Yu.M. Shernyakov, A. F. Tsatsul'nikov, V. M. Ustinov, B.V. Volovik, A. E. Zhukov, Zh. I. Alferov, N. N. Ledentsov and D. Bimberg, Proceedings ICPS24, Jerusalem, 1998, D. Gershoni, Ed. (World Scientific, 1999).

11:00 AM

Collisional Carrier Kinetics and Broadening of Spectral Lines in Quantum Dot Structures: *Alexander V. Uskov*[1]; [1]Lebedev Physical Institute, Div. of Quantum Radio Phys., Leninsky pr 53, 117924 Moscow Russia

Self-Assembled Quantum Dot (SAQD) semiconductor lasers attract much attention due to their interesting physics and potential applications. In these lasers, carriers are pumped into barriers around the Quantum Dots (QDs), and then are captured by the QDs, and relax via QD energy levels to the low-lying lasing ones. These relaxation processes can strongly affect laser characteristics, and are currently under intense study. While in quantum well (QW) lasers fast carrier capture and relaxation are mediated by carrier-LO phonon interactions, in QD structures carrier relaxation via LO phonon scattering is highly improbable due to the discrete nature of the QD energy levels and the fixed energies of LO phonons. Therefore, observed in SAQD structures carrier capture and relaxation with characteristic times ~1-100 ps is ascribed, at least, in part to carrier-carrier Coulomb collisions in SAQD structures. In the present work, carrier capture into SAQDs and their subsequent relaxation in them due to carrier-carrier Coulomb interactions is under consideration. Rate equations, which describe these carrier kinetics, are formulated, and the calculated rate constants for carrier capture and carrier relaxation are given. Numerical examples demonstrate that the carrier capture time and carrier relaxation times can be ~1-100 ps in dependence on carrier density in wetting layer of SAQD structure. Laser behavior and characteristics (mode competition and modulation characteristics, for instance) can depend not only on carrier relaxation times in laser structure, but also on the dephasing time T_2 of lasing transition. The dephasing time for QDs similarly to bulks and QWs is defined by interactions of QD carriers with surrounding phonons and carriers. The homogeneous linewidth ???g_h<0.1meV (g_h=1/T_2) have been observed in photoluminescence of single QDs at low temperatures, and have been ascribed to carrier-acoustic phonon interactions. In room-temperature QD lasers with carrier injection, many carriers can surround QDs, and their interactions with QD carriers are able to lead to substantial broadening of optical transitions in QDs. Results of calculation of homogeneous broadening (i.e. the dephasing time T_2) and shift of spectral lines in SAQD due to elastic Coulomb collisions between carriers in SAQD structures are given in the present work. According to the calculations, collisions of 2D carriers of wetting layers with SAQDs can lead to the dephasing time T_2<1ps at the carriers densities N~10^{15} m^{-2}. The time is much shorter than collisional carrier relaxation times in QDs at the same carrier densities. The situation, when homogeneous broadening is defined rather by dephasing elastic collisions then by inelastic collisions, is typical for atomic gases.

11:20 AM +

Direct Bandgap Materials for Monolithic Optical Interconnects on Silicon: *Victoria Ann Williams*[1]; Alfred T. Schremer[1]; Joseph M. Ballantyne[1]; [1]Cornell University, Elect. Eng., Ithaca, NY 14850 USA

An optical databus could be used to increase data transmission rates and lower power consumption for off-chip communications. The main

limitation to realizing this optical interconnect technology is the lack of a high-quality, light-emitting material that can be monolithically integrated with silicon electronics. Our group has recently investigated one approach to solving this problem. Initial results indicated that the (Al)GaP system may be deposited directly on silicon by selective area epitaxy MOCVD. Additionally, it was shown that GaInP deposited on GaP substrates by MOCVD formed strain-induced quantum islands with efficient luminescence. By combining the (Al)GaP/Si and GaInP/GaP technologies, it may be possible for high quality optical material to be deposited on silicon. Several aspects of the research on the GaInP quantum islands will be presented. Optimization of growth conditions has produced a 10X improvement in the photoluminescence intensities, compared with that previously reported by this group. Also, as a first step toward integrating the GaInP system on silicon, the deposition of GaInP on patterned GaP substrates has been investigated. The dimensions of the mask features were found to have an effect on island density, as well as the intensity of the photoluminescence peak and the emission wavelength. Larger mask dimensions produced a larger density of islands and an increased photoluminescence intensity. Laser structures grown on GaP substrates and containing a GaInP active region with AlGaP cladding layers have been optically pumped with a nitrogen laser to measure the amount of gain in the waveguide, which will determine the suitability of this material for optoelectronic devices. Stimulated emission has been observed in these structures.

11:40 AM Late News

Session B. Materials Integration - Substrate Fabrication and Bonding

Wednesday AM   Room: State Street Room
June 30, 1999   Location: University Center

Session Chairs: Pete Moran, University of Wisconsin-Madison, Dept. of Chem. Eng., Madison, WI USA; Alan Doolittle, Georgia Institute of Technology, Atlanta, GA USA

10:00 AM +
Fabrication of Thin Film InGaN LED Membranes by Laser Liftoff:
William S. Wong[1]; Nathan W. Cheung[2]; Timothy D. Sands[3]; Michael Kneissl[4]; David P. Bour[4]; Ping Mei[4]; Linda T. Romano[4]; Noble M. Johnson[4]; [1]University of California, Dept. of Mats. Sci. and Min. Eng., 211-181 Cory Hall, #1772, Berkeley, CA 94720-1772 USA; [2]University of California, Dept. of Elect. Eng. and Comp. Sci., 513 Cory Hall, Berkeley, CA 94720 USA; [3]University of California, Dept. of Mats. Sci. and Min. Eng., 559 Evans Hall, Berkeley, CA 94720-1760 USA; [4]Xerox PARC, Electr. Mats. Lab., 3333 Coyote Hill Rd., Palo Alto, CA 94304 USA

The rapid development of GaN based light-emitting diodes (LED) and laser diodes (LD) has impelled a tremendous increase in group III nitride research. As a result of this swift progress, GaN based high-brightness blue LEDs, and more recently, blue LDs have become commercially available. Despite the rapid advances, the most commonly used growth substrate, sapphire, still imposes constraints on GaN film quality due to the lattice and thermal expansion coefficient mismatch between the sapphire and GaN. In addition, the sapphire constraint inhibits LED and LD device performance due to the poor thermal and electrical conductivity of the substrate. To alleviate the substrate constraint, we have developed a laser liftoff technique to separate GaN thin films from its growth sapphire substrate, and create free-standing GaN membranes. As a demonstration of this laser liftoff process, InGaN-based LEDs, prefabricated on sapphire substrates, have been bonded and transferred onto Si substrates by pulsed UV-laser processing. The thin film InGaN LED structures on sapphire were initially bonded onto the Si substrate with a polymer based adhesive. A single 600 mJ/cm^2, 38 ns KrF excimer laser pulse was directed through the transparent substrate to induce a rapid thermal decomposition of the GaN at the GaN/sapphire interface. The decomposition yields metallic Ga and N_2 gas that allows separation of the GaN film from the substrate. Free-standing InGaN LED membranes were fabricated by immersing the InGaN LED/adhesive/Si structure in acetone to dissolve the glue bond. Characterization of the InGaN LED before and after the sapphire substrate removal showed no measurable degradation in device performance. Current-voltage measurements of the LED membranes showed the diode turn on voltage to remain unchanged after liftoff. The room-temperature emission spectra at a 10 mA dc forward current exhibited no change before and after liftoff with a peak emission wavelength at 389 nm and a spectral full-width at half maximum of 10 nm. Light output for the LED membrane was 4 mW at a 100 mA forward current with an external quantum efficiency of ~1.3%. The advancements made in GaN growth and device processing on sapphire combined with the laser liftoff technique will allow direct integration of GaN with more accordant substrate materials for improved device performance.

10:20 AM +
GaN LEDs Transferred to Copper Substrates Using Laser Assisted Debonding:
Philip R. Tavernier[1]; Monica C. Hansen[1]; Steve P. DenBaars[1]; David R. Clarke[1]; [1]University of California Santa Barbara, Dept. of Mats., Bldg. 503, Rm. 1355, Santa Barbara, CA 93106-5050 USA

GaN light emitting diodes grown on sapphire substrates have been successfully transferred to copper substrates after laser assisted debonding. The use of high-energy pulses from a UV/Excimer laser system allows the original sapphire substrate to be removed and substituted with any number of more thermally conductive materials. Although electrical and optical characterizations of this novel device structure shows some deterioration in the I-V characteristics, no significant degradation in optical intensity was found suggesting that the transfer process is viable for future applications.

10:40 AM +
A Comparison of Wet and Dry Chemistries for Hydrophobic Silicon Wafer Bonding:
James B. Mattzela[1]; Paul A. Roman[1]; Jerzy Ruzyllo[1]; Theresa S. Mayer[1]; [1]The Pennsylvania State University, Dept. of Elect. Eng., University Park, PA 16802

Hydrophobic silicon wafer bonding has been investigated for the high quality electrical interface it produces, which lends itself to the fabrication of novel power devices such as dual gated insulated gate bipolar junction transistors (IGBTs) and MOS controlled thyristors (MCTs). As improvements are made in silicon surface preparation for integrated circuit (IC) manufacturing, the resulting techniques can also be applied such as silicon wafer bonding. One recent advance in silicon surface preparation has been the move from surface cleaning processes to surface conditioning processes. These new processes are complementing wet surface cleaning chemistries with similar dry (gas phase) surface conditioning chemistries [1]. The dry phase processing has many advantages over current wet procedures that can be utilized for wafer bonding applications - smaller amount of chemicals consumed, less direct contact between personnel and wafers, and the vacuum environment lends itself to usage in a "cluster" tool environment. In addition, the surface termination left by gas phase processing is more controllable and more reproducible than that obtained on wet processed surfaces. In this talk, we will compare the quality of hydrophobic silicon wafer bonds obtained on samples prepared using wet and dry chemistries. The wet processed samples were prepared using traditional silicon cleaning techniques, which consisted of a Standard Clean 1 (SC1) followed by a Standard Clean 2 (SC2) to remove particulate and metallic contamination. The surfaces were rendered hydrophobic by dipping the samples into a 1% hydrofluoric acid (HF) solution immediately prior to room-temperature bonding. The dry processed wafer pairs were cleaned with SC1 to remove particulate contamination prior to loading into a commercially available dry cleaning module. Once loaded, the dry cleaning procedure consisted of anhydrous HF etch to remove the native oxides remaining on the silicon surface followed by a "rinse"

in gaseous methanol. It was demonstrated previously that the surface termination and rms roughness of such dry processed wafers is similar to that obtained by wet cleaning [1]. For both the wet and dry processed samples, wafer bonding was initiated at room-temperature by applying a point source of pressure to the silicon wafers. Following room-temperature bonding, the samples were annealed at 1100°C in N_2 for 2.5 hours to strengthen the bonded interface. The surface energy of the bonds were measured using the crack method and were determined to be approximately 1600 and 1580 ergs/cm^{2} for the wet and dry processed wafers, respectively. This suggests that gas phase surface conditioning is a viable alternative to wet cleaning chemistries for preparation of silicon for applications requiring hydrophobic silicon wafer bonding. [1] M. Heyns, P. Mertens, J. Ruzyllo, and M.Y.M. Lee, Solid State Technology, 42 (3), 37 (1999).

11:00 AM +
Deposition of Borosilicate Glasses by Low Pressure Chemical Vapor Deposition Using Tetraethylorthosilicate and Trimethylborate: *Darren Michael Hansen*[1]; David Charters[1]; Yee Au[1]; Wai Mak[1]; Wisnu Tejasukmana[1]; Peter D. Moran[1]; Thomas F. Kuech[1]; [1]University of Wisconsin, Chem. Eng., 1415 Eng. Dr., Madison, WI 53706 USA

Borosilicate glass (BSG) has many desirable properties required in semiconductor device processing applications. BSGs possess a composition-dependent viscosity which is much lower than silicon dioxide and has been investigated as a means of reducing the thermal budget associated with planarization using glass reflow. In addition, the composition-dependent viscosity is being used in the development of a compliant substrate. These compliant substrates employ the BSG as a medium to support a thin template layer on a thicker handle wafer. We have studied the BSG deposition of over a wide range of conditions and compositions. The deposition of BSG was investigated using low-pressure chemical vapor deposition, at pressures around 1 Torr, utilizing tetraethylortho silicate (TEOS) and trimethylborate (TMB) as the precursor materials. Deposition of silicon dioxide using TEOS is a well-studied system and our investigations are consistent with those of previous investigations revealing that the deposition process is reaction rate-limited with an apparent activation energy, Ea, of 56±8 kcal/mol over the temperature range 650-710°C. The morphology, as measured with atomic force microscopy (AFM), and the uniformity of the grown layer impact the quality of bonding for compliant substrate applications and were found to be a function of the reactor conditions such as temperature and pressure. The deposition of the BSG, $(SiO2)x(B2O3)1-x$, was investigated over the entire composition range, i.e. 0<x<1. Growth of high boron-content BSG (x>0.20) is not a well-understood process. This is due, in part, to the reaction of high boron oxide content glass with water forming boric acid on the glass surface in the room ambient, leading to film degradation. Measurement of the apparent activation energy for the reaction for different BSG compositions indicates an activated process as the rate limiting step with a measured apparent activation energy of Ea=53±7 and 66±5 kcal/mol for x=0.84 and 0.50, respectively. This result is consistent with the observation that the deposition rate was found to be independent of reactor space-time, i.e. the residence time of the precursors within the reactor volume. Proposed decomposition pathways leading to BSG deposition from these precursors will be presented. In addition, the morphology and uniformity were discovered to be excellent for a wide range of x values and reactor conditions. Typical rms roughness values for the as deposited glass were ~0.50 nm over a 5 μm square window as determined by AFM with a thickness uniformity which is typically better than ±10% over a 3" wafer. These results have allowed the use of BSG in the development of compliant substrates.

11:20 AM
Ion-Cutting of GaSb Wafers: *Y. Zheng*[1]; Z. F. Guan[1]; S. S. Lau[1]; D. M. Hansen[2]; T. F. Kuech[2]; T. E. Haynes[3]; T. Hoechbauer[4]; M. Nastasi[4]; [1]University of California, San Diego, Dept. of Elect. and Comp. Eng., 9500 Gilman Dr., Mail Code 0407, La Jolla, CA 92093-0407 USA; [2]University of Wisconsin-Madison, Dept. of Chem. Eng., Madison, WI 53706-1691 USA; [3]Oak Ridge National Laboratory, Solid State Div., Oak Ridge, TN 37831 USA; [4]Los Alamos National Laboratory, Mats. Sci. & Tech. Div., Los Alamos, NM 87545 USA

GaSb based structures are of potential interest in the fabrication of microwave devices. This can be seen in the case of InGaSb, which has been proposed as an ideal material for transferred-electron devices. In such a device, a semi-insulating substrate lattice-matched to InGaSb is required. GaSb seems to be the obvious choice. However, semi-insulating GaSb wafers are currently not available. One way to solve this problem is to grow a thin layer of GaSb on a semi-insulating substrate, e.g. GaAs. However, in this process, lattice mismatch has an influence on the quality of the grown GaSb layer. An alternative way is to transfer a thin layer of GaSb onto an insulator using Ion-cutting. In this technique, H and/or He ions are implanted in a GaSb wafer with a dose of a few times 10^{16} cm^{-2}, followed by bonding to a stiffening wafer coated with an insulator. Upon appropriate annealing, a thin layer of GaSb is transferred onto the insulator, thus serving as a template for further growth of semiconductor layers, e.g. InGaSb. In this study, n-type (100) GaSb wafers, Te doped with a dopant level of $7x10^{17}$ cm[-3], were implanted with 150 keV H and He ions, respectively, at various doses. We found that blistering occurred readily in both H and He implanted samples. The surface bubbles showed a tendency to coalesce to form large areas of exfoliation. This can be clearly seen in samples annealed faced down on a smooth substrate, where an entire surface layer was exfoliated from the GaSb substrate, in marked contrast to the blistering phenomenon of hydrogen-implanted silicon wafers. The tendency of the H- and He- implants in GaSb to form large-area exfoliation without bonding indicates a less stringent requirement on the bonding strength between GaSb and the stiffening wafer. However, low temperature hydrophilic bonding (typically < 400°C) of GaSb to other substrates proved to be difficult, due to the poor wafer surface quality and the difficulties in providing hydrophilic surfaces. Our preliminary results showed that the bonding of GaSb wafers could be facilitated by an appropriate bonding medium. The transfer of GaSb surface layer onto an insulator was demonstrated for the first time by using flowable oxide as the bonding medium. Possible ways of improving bonding quality will be discussed. *Acknowledgement: A portion of this work was performed at Oak Ridge National Laboratory and sponsored by the U.S. Dept. of Energy, Div. of Mats. Scis., under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation The work at Los Alamos National Laboratory was supported by the US Dept. of Energy, Office of Basic Energy Sciences, Div. of Material Sciences.

11:40 AM Late News

Session C. Characterization, Growth and Properties of Organic Electronic Materials

Wednesday AM   Room: Santa Barbara Harbor
June 30, 1999   Location: University Center

Session Chairs: Jianna Wang, Penn State University, Dept. of Elect. Eng., State College, PA USA; Rashid Bashir, Purdue University, School of Elect. and Comp. Eng., West Lafayette, IN USA

10:00 AM
Dependence of Emission Quantum Yield on Chain Packing in Electroluminescent Polymers: *Lewis J. Rothberg*[1]; Christopher J. Collsion[1]; Rachel Jakubiak[1]; Yi Li[1]; Christine M. Liberatore[1]; EdVin Soh[1]; [1]University of Rochester, Dept. of Chemistry/NSF Center for Photoinduced Charge Transfer, Hutchison Hall 200, Rochester, NY 14627 USA

The efficiency of organic light-emitting diodes depends on the emission quantum yield of the lowest excited singlet state. Aggregation quenching of luminescence in fluorescent dyes is commonly observed

in the solid state. This phenomenon is less prevalent in emissive polymers but solid state luminescence in neat conjugated polymer films is still much less than in dilute solution. Moreover, luminescence yields and lasing thresholds depend strongly on processing conditions, suggesting the importance of polymer morphology in the photophysics. We report a study of soluble substituted phenylenevinylene polymers in solution that addresses the relationship between order and luminescence quantum yield. Deliberate aggregation of the polymer MEH-PPV in bad solvents leads to film-like spectra and low quantum yields. Our results indicate that polymer chains behave in two distinct ways depending on their local ordering. One set of chains produces high fluorescence quantum yield blue emission characteristic of good solvents and a second set of chains emits similarly structured red shifted luminescence characteristic of bad solvent environments. All of the samples we have studied can be well represented by a superposition of these two discrete populations. We have characterized these extreme cases using optical methods and nuclear magnetic resonance and concluded that the primary explanation of the spectroscopic difference is increased conjugation length in bad solvent due to steric suppression of torsional motion caused by packing of the polymers. The reduction of photoluminescence in bad solvents does not coincide with a substantial reduction of the excited singlet state lifetime. Instead, we believe that the reduced quantum yield in these packed regions is due to interchain interactions that lead to rapid formation of excimers that do not have significant quantum yield for emission. We will present evidence for these from transient absorption and luminescence measurements. These results are especially important since they are prescriptive for synthetic design of the polymers. In addition, characterizing order in solution is essential in understanding the factors that determine the efficacy of different processing methodologies.

10:20 AM +

Near-Field Scanning Optical Microscopy of Conjugated Polymer Films: *Jessie A. DeAro*[1]; Paul J. Carson[1]; Jonathon Z. Sexton[1]; Steven K. Buratto[1]; [1]University of California, Santa Barbara, Chemistry Dept., Santa Barbara, CA 93106 USA

We will discuss the application of Near-Field Scanning Optical Microscopy (NSOM) and Near-Field Optical Spectroscopy (NFOS) to the investigation of the mesoscale (10-100nm) optical, transport and photochemical properties of semiconducting polymers such as poly(p-phenylene vinylene) (PPV). Photoluminescence (PL), linear dichroism, photo-oxidation and photoconductivity NSOM experiments on conjugated polymer films show a strong dependence of these properties on the local (50nm) film morphology. Blends of stretch-oriented MEH-PPV and ultra high-density polyethylene show 50nm domains of phase separation directly related to the film morphology. Spatial hole burning NSOM experiments measure the carrier diffusion in poly(2-methoxy-5-(2'-ethyl-hexyloxy)-1,4-phenylene vinylene) (MEH-PPV) thin films. This technique provides a tool for nanoscale photo-patterning, the resulting pattern is sensitive to ambient conditions, heat transport, carrier diffusion and local film morphology. PL spectra, collected concurrently with the photo-oxidation pattern, show a changing PL profile versus exposure time. Single polymer molecule experiments of MEH-PPV will also be discussed.

10:40 AM

CPAFM: A Tool for Nanoscale Structure and Electronic Properties: *Tommie Wilson Kelley*[1]; C. Daniel Frisbie[2]; [1]University of Minnesota, Chem. Eng. and Mats. Sci., 421 Washington Ave. SE, 151 Amundson Hall, Box 134, Minneapolis, MN 55455 USA; [2]University of Minnesota, Chem. Eng. and Mats. Sci., 421 Washington Ave. SE, 151 Amundson Hall, Minneapolis, MN 55455 USA

Conducting Probe Atomic Force Microscopy, (CP-AFM), is a valuable characterization tool for relating microstructure of organic thin films to their electrical properties. Our current research focuses on the crystalline organic semiconductor a-sexithiophene, which is vacuum deposited as single crystals (1-5 molecular layers in thickness and hundreds of nanometers to several microns in spatial extent) onto insulating substrates that have been photo- and nano-lithographically patterned with Au electrodes. A Au-coated AFM probe is then used to image each crystal, including defects, and to subsequently make point-contact electrical measurements at particular positions on each crystal.

Current-voltage (I-V) curves are recorded as a function of probe-electrode separation. From these data, one can estimate the tip-crystal contact resistance as well as the conductivity of each crystal. Our most recent measurements are geared toward quantifying the dependence of the I-V characteristics on crystal thickness as well as mapping the electronic properties of individual defects (e.g. grain boundaries). Plots of Resistance (R=V/I for a particular point on each I-V trace) vs. tip-electrode separation (L) can be used to estimate the contact resistance of the tip to each crystal. Defects, such as junctions or constrictions in the crystal are manifested as a change in slope on the R vs L plot. Log I vs Log V plots can also be constructed to estimate the conductivity and the extent of trapping in each crystal. Finite Element modeling is being performed concurrently to increase the physical understanding of our data and to relate it to applicable theory (e.g. Space Charge Limited Current, SCLC). Heightened interest in molecule-based electronics has underscored the need for better understanding of conduction mechanisms in organic materials, particularly in thin film form. CP-AFM offers a unique method of correlating the supramolecular structure with the electronic properties of thin, organic semiconductors.

11:00 AM +

Growth of Thermally Evaporated Pentacene Films on SiO2: *Jonathan Andrew Nichols*[1]; David James Gundlach[1]; Chris D. Sheraw[1]; Darrell G. Schlom[2]; Thomas Nelson Jackson[1]; [1]The Pennsylvania State University, Dept. of Elect. Eng., 121 Elect. Eng. East, University Park, PA 16802 USA; [2]The Pennsylvania State University, Dept. of Mats. Sci. and Eng., 103 Steidle Bldg., University Park, PA 16802 USA

Pentacene has been used to fabricate thin film transistors with performance comparable to devices using hydrogenated amorphous silicon; such devices are of interest for use in displays and other broad area electronic applications. Thermally evaporated pentacene films often show significant ordering and the morphology of deposited films appears to have a strong influence on the device characteristics. In this study, pentacene films thermally evaporated onto substrates held at different temperatures were examined using atomic force microscopy (AFM). All of the investigated films were deposited onto bare silicon dioxide (thermally oxidized silicon, rms roughness < 0.2 nm) at relatively slow deposition rates (0.01-0.06 nm/s). Film nucleation was studied by comparing images of substrates exposed to the same total dose (1 nm average thickness on a water-cooled quartz crystal microbalance) of evaporated pentacene deposited at various substrate temperatures. It was found that as the substrate temperature is increased, the nucleation density decreases from $\sim 1 \times 10^8$ cm^{-2} at 30°C to $\sim 2 \times 10^7$ cm//bdp/-2 at 75°C while the grain size increases from ~ 0.25 mm at 30°C to ~ 2 mm at 75°C. The nuclei are one molecular layer high (~ 1.5 nm). At 75°C, the grains, which consisted of micron-sized branches, look significantly more dendritic than those deposited at lower temperatures. The examination of progressively thicker films revealed that the pentacene nuclei grow and coalesce, eventually creating a connected network, one molecular layer in height, containing isolated voids. This is followed by similar layered growth until eventually a switch to island growth occurs. The thickness at which the transition in this Stranski-Krastanov growth takes place appears to be dependent on the substrate temperature. An increase in the adsorbed molecule surface mobility at higher temperatures allowed better ordering within and between the grains and resulted in the observation of distinct faceting in 90°C, 50 nm average thickness films. At higher substrate temperatures, the sticking coefficient decreased and film nucleation was more difficult.

11:20 AM

Nanoscale Investigation of the Optical Properties of Tris-8-Hydroxyquinoline Aluminum Films (Alq$_3$): *Grace M. Credo*[1]; Steven K. Buratto[1]; [1]UC Santa Barbara, Dept. of Chemistry, Santa Barbara, CA 93106-9510 USA

For the past decade, thin films of the luminescent organic semiconductor tris-8-hydroxyquinoline aluminum (Alq$_3$) have been widely studied due to their tremendous potential as the active layer in organic light-emitting devices. Despite the numerous spectroscopy techniques applied to Alq$_3$ films, the dependence of the optical properties on film morphology, particularly on a sub-micron level, remain poorly understood. The principal reason for this is that previous studies rely on far-

field spectroscopy techniques which average over many morphological domains. In order to overcome this drawback, we use confocal and near-field scanning optical microscopy (NSOM) to probe carrier transport and diffusion length in Alq_3 vacuum-deposited films with 10-100 nm resolution, the length scale of many interesting structural domains. We use concurrent shear force microscopy (an analog to atomic force microscopy, AFM) to correlate morphology (crystalline vs. amorphous regions) to intensity variations in our fluorescence images as well as variations in the localized fluorescence spectra. Our results lead to a better understanding of how the nanoscale structure in Alq_3 affects its optical properties.

11:40 AM   Late News

Session D. Oxides for Devices

Wednesday AM   Room: Flying A Studios
June 30, 1999   Location: University Center

Session Chair: Dan Dapkus, University of Southern California, Los Angeles, CA USA

10:00 AM   +
Increased Lateral Oxidation Rates of AlInAs on InP Using Short-Period Superlattices: *Eric Hall*[1]; Andrew Huntington[1]; Ryan Naone[1]; Herbert Kroemer[2]; Larry A. Coldren[2]; [1]Universitiy of California, Santa Barbara, Mats. Dept., Santa Barbara, CA 93106 USA; [2]University of California, Santa Barbara, ECE Dept., Santa Barbara, CA 93106 USA

The wet thermal oxidation of AlGaAs compounds has found many useful applications in GaAs-based devices. For InP-based devices, however, similar progress has been limited by the absence of a suitable oxidation material lattice-matched to this substrate. The oxidation of lattice-matched AlAsSb compounds has been found to leave an elemental antimony layer at the oxide-semiconductor interface [1], and the low Al mole fraction of lattice-matched AlInAs slows oxidation rates and demands higher temperatures. [2] We present greatly increased lateral oxidation rates for AlInAs grown as a short-period superlattice of InAs and AlAs compared to the analog alloy. The tensile strain in the AlAs layers is balanced by the compressive strain in the InAs layers, creating a strain-compensated alloy lattice-matched to InP. Oxidation layers with superlattice periods up to 40Å and cladded by lattice-matched InGaAs layers were grown on InP substrates and laterally oxidized at temperatures ranging from 450°C to 550°C. The oxidation depth for a given time and temperature was seen to increase with superlattice period. For a period of 40Å, an oxidation temperature of 525°C, and an oxidation time of one hour, the superlattice had oxidized over 6μm while the analog alloy had only oxidized ~2μm. The same oxidation depth as the analog alloy for these conditions could be achieved, in fact, with the superlattice at a temperature of 475°C. The oxidized superlattices were examined using cross-sectional transmission electron microscopy. The longer-period superlattices (40Å) showed a very non-uniform oxide front with the oxide confined to the AlAs layers and the InAs layers remaining unoxidized. For shorter superlattice periods (20Å), the superlattice is no longer visible in the oxidized region and the front is more uniform. This work was supported by the Heterogeneous Optoelectronics Technology Center. [1] O. Blum et al., Appl. Phys. Let. 68, 3129 (1996) [2] H. Gebretsadik et al., Appl. Phys. Let. 72, 135 (1988)

10:20 AM   +
As Overpressure Mediated Crystallinity Change of AlGaAs Compounds and its Application in Formation of Bragg Reflectors: *Kuo-Lih Chang*[1]; D. E. Wohlert[1]; G. W. Pickrell[1]; J. H. Epple[1]; H. C. Lin[1]; K. Y. Cheng[1]; K. C. Hsieh[1]; [1]University of Illinois at Urbana-Champaign, Dept. of Elect. and Comp. Eng., Urbana, IL 61801 USA

Native oxide formed by wet vapor oxidation of crystalline Al-bearing compound semiconductors has been used for many applications in optoelectronic devices, such as current confinement and distributed Bragg reflectors (DBRs) of vertical cavity surface emitting lasers (VCSELs). We have demonstrated in our previous work the formation of amorphous Al-bearing compound semiconductor grown on GaAs, InP, and GaP substrates by molecular beam epitaxy (MBE) at low temperatures. In this work, a new technology is presented to control the crystallinity of AlGaAs compound and to demonstrate its application as the DBRs of VCSELs, which are formed by lateral wet vapor oxidation. Samples of (Ga,As) and (Al,As) layers were grown with MBE on GaP substrate at low temperatures around 100°C, with different As pressures: 5E-7, 2E-7, and 8E-8 torr. Deposited at higher As overpressure of 5E-7 and 2E-7 torr, the (Ga,As) and (Al,As) compounds remain amorphous. Auger Electron Spectroscopy (AES) indicates that excess 50% and 30% As are incorporated in the film respectively. The higher As incorporation is attributed to the higher As overpressure. Deposited at 8E-8 torr, however, the (Ga,As) and (Al,As) become polycrystalline and there is no obvious interface between these two layers. Wet oxidation has been conducted on the samples at 350°C for 1 hour. The as-grown amorphous (Al,As) layers become aluminum oxide while the amorphous (Ga,As) becomes a mixture of gallium oxide and (Ga,As) crystalline. In contrast, the poly-crystalline as-grown film remains polycrystalline arsenide compounds because of slow oxidation rate at low temperatures. The thickness of AlxOy shrinks to 80% to 85% of the original of AlAs. Better mechanical strength can be obtained by annealing the oxidized sample at 650°C for 45 minutes. In-situ annealing and ampule seal technique (without water vapor) have been used to verify the recrystallization of amorphous (Al,As) and (Ga,As) at 420°C for 20 minutes, and solid state epitaxy has been observed near the substrate interface. The large difference in oxidation rate at low temperatures between polycrystalline GaAs and amorphous (Al,As) allows us to fabricate a high reflectance Bragg reflector suitable for 1.55 um semiconductor laser. To achieve that we have deposited several pairs of poly-GaAs and amorphous-AlAs on InP substrates by controlling the As overpressure in MBE. Conventional photolithography and reaction ion etching (RIE) have been applied to delineate stripes of 125 um wide and complete lateral oxidation has been accomplished at 350°C for 14 hours. The high reflectivity obtained from those oxide/semiconductor pairs indicates that it is a promising technology for the realization of DBRs.

10:40 AM   +
The Effect of an Oxide Aperature on the Base-Collector Capacitance of a GaAs Heterojunction Bipolar Transistor: *James G. Champlain*[1]; Umesh K. Mishra[1]; [1]University of California, Elect. and Comp. Eng., Santa Barbara, CA 93106 USA

In an effort to increase the frequency performance, namely the current-gain cutoff frequency (f_t) and maximum frequency of oscillation (f_{max}), of GaAs heterojunction bipolar transistors (HBTs) parasitic components of the transistor, such as base resistance (R_B) and base-collector capacitance (C_{BC}), must be reduced. To this end, many groups have attempted to reduce C_{BC} using flip-chip processes which allow the physical reduction of the collector area and have succeeded with great results. But commonly these processes are involved and increase the complexity of the overall fabrication. In this paper we propose a method of reducing the C_{BC} of an HBT by the partial oxidation of the collector. Given that the relative permittivity of GaAs/AlAs is 13.2/ 10.9 and Al_2O_3 (resulting from the oxidation of $Al_xGa_{1-x}As$, x > 0.96) is approximately 5.8, by this method it is theoretically possible to reduce C_{BC} by a factor of nearly two, depending upon layer structure and device geometry. But unlike flip-chip processes, this method requires no additional processing and offers similar results in performance. For this experiment, base-collector structures, similar to those in the proposed HBT, were grown by molecular beam epitaxy (MBE). The layer structure consists of an 6000 Å n+ (Si: 4 x 10^{18} /cm³) GaAs sub-collector/ buffer grown on a semi-insulating GaAs substrate, followed by a 2500 Å $Al_{0.98}Ga_{0.02}As$ collector, a 2500 Å linear grade to GaAs, a 500 Å p+ (Be: 1 x 10^{19} /cm³) GaAs base, and a 30 Å AlAs etch-stop with a 200 Å GaAs protective cap for oxidation. Large area capacitor mesas were fabricated using standard photolithography and Cl₂ reactive-ion etching (RIE). This was followed by oxidation at 425°C for 10, 20, 30, 45, 60,

and 120 minutes. Finally, the protective cap was removed by a wet etch and Ti/Pt/Au contacts were deposited onto the base and collector by e-beam evaporation. For this experiment, large area (high capacitance) capacitors were used to facilitate easy measurement and comparison of total capacitances. Our results show that by partial oxidation of the collector the total capacitance of the base-collector structure is reduced. For greater oxidation times, and therefore a larger oxidized area, smaller capacitances may be achieved. For an unoxidized sample the total capacitance is 115 pF, whereas for the sample oxidized for 120 minutes the total capacitance is reduced to 92.9 pF. This reduction in capacitance can be modeled as a simple capacitor network with capacitors for unoxidized and oxidized material tied in parallel, and predicts the trend seen in our experiment. There are also no adverse affects on the current-voltage characteristics of these diodes due to the oxidation. Future work is planned to examine the base-collector layer structure design in an attempt to optimize the effect on the reduction of C_{BC}. This work supported by NCEE contract F33615-95-C-1755.

11:00 AM +
Electrical Properties of Al2O3 Gate Dielectric: *Chin Chang Liao*[1]; W. J. Chen; C. H. Lu[1]; Albert Chin[1]; C. Tsai[1]; [1]National Chiao Tung University, Dept. of Electronics Eng., Hsinchu Taiwan; National Huwei Inst. Tech, Dept. of Mechanical Mats. Eng., Huwei Taiwan

To continuously improve the MOSFET device performance, alternative high-K gate dielectric other than SiO2 is urgently required. This alternative dielectric must have the high K, low leakage current, low interface-charge density, good breakdown field and reliability. Although Si3N4 has attracted much attention, but the application to VLSI can only last only one or two generation due to its relatively large leakage current. Recently, we have studied the Al2O3 as an alternative gate dielectric by direct oxidation of deposited Al. The native oxide is removed in-situ using ultra-high vacuum MBE before Al evaporation [1]. Similar Al2O3 by sputtering is also reported by Manchanda et al from Bell Labs at IEDM [2]. However, in spite of the leakage current and K-value, both of these two papers do not present more detailed mobility, reliability and device data that is important to further integrate Al2O3 into VLSI. In this work, we report the detailed electrical characterization of Al2O3 gate dielectric. We have also fabricated MOSFET using Al2O3 gate dielectric to measure the electron mobility. We have found that the presence of native oxide can severely reduce the K-value and native oxide is suppressed by HF-vapor passivation or UHV desorption. Similar idea has been applied by us to achieve the atomically smooth ultra-thin oxide with good electrical characteristics and reliability. A low temperature oxidation followed by a high temperature annealing in nitrogen is used to reduce Al and Si inter-diffusion. The formation of Al2O3 is confirmed by SIMS measurement. The leakage current of the 4.8 nm Al2O3 capacitor is ~6 order of magnitude lower than that of the equivalent thermal SiO2. From C-V measurement, a K of ~8.5 is obtained in an 11 nm thick Al2O3 capacitor and a low mid-gap interface trap density of 1¡Ñ1011 eV/cm2 is achieved. This low Dit value is further demonstrated by measuring the inversion layer mobility of a MOSFET. The measured electron mobility of an 8 nm Al2O3 MOSFET is compatible to that of thermal SiO2 over a large gate field. The good reliability of the 4.8 nm Al2O3 gate dielectric is evidenced from the small stress-induced leakage current after a 2.5V constant stress for 10,000 sec. We believe that the good reliability is due to the direct Al thermal oxidation. Because this process is similar to thermal SiO2, any possible process-related damage in Al2O3 can be minimized.

11:20 AM Late News

11:40 AM Late News

Session E. Special Topical Session

Wednesday PM   Room: Lotte Lehman Hall
June 30, 1999   Location: Music Building

Session Chairs: Jim Speck, University of California, Mats. Dept., Santa Barbara, CA USA; Richard Miles, SDL Inc., San Jose, CA USA

1:30 PM *Invited
Electron Microscope Studies of Defects, Piezoelectric Fields and Microscopic Luminescence in InGaN/GaN Films: *D. Cherns*[1]; [1]University of Bristol, H. H. Wills Physics Laboratory, Tyndall Ave., Bristol BS8 1TL UK

This paper will describe the analysis of the microstructure of InGaN/GaN films by a range of electron microscope techniques, including imaging, diffraction and electron holography in the transmission electron microscope (TEM) and cathodoluminescence in the scanning electron microscope (SEMCL). The analysis of dislocations, nanopipes and inversion domains in MOCVD GaN/(0001) sapphire by TEM is briefly reviewed and some remaining problems are highlighted. Recent work is then described in which electron holography has been used to measure piezoelectric fields across strained InGaN quantum wells in GaN. For example, the field across a 1.5nm In0.52Ga0.48N quantum well was measured as 4MV cm-1 corresponding to a potential drop of 0.6V across the well. Recent SEMCL studies are also described in which we have examined the luminescence from individual threading defects in InGaN/GaN quantum well structures. The paper will discuss how the combined results of the TEM, electron holography and SEMCL contribute to our understanding of how the microstructure of InGaN/GaN films affects luminescence properties.

2:00 PM *Invited
The Technological Significance of Defects in III-Nitride Materials: *S. Jeffrey Rosner*[1]; [1]Hewlett-Packard Laboratories, 3500 Deer Creek Rd., Palo Alto, CA 94303

Defects in semiconductors for optoelectronic applications are a fruitful topic for study by materials scientists and solid state physicists. It has long been held as conventional wisdom that unintentionally introduced extended defects such as dislocations and stacking faults have deleterious effects on the minority carrier populations in such materials, creating built-in electric fields and providing large cross-sections for non-radiative recombination. Strain related slip relaxation has often been the casual mechanism, but additional difficulties with epitaxial growth and device processing have also been found to introduce such defects. It has nearly always been difficult to fabricate high performance minority-carrier devices in semiconductor materials with high concentrations (> 1E5 cm-2) of extended defects. Over the past five years, there have been many significant demonstrations in GaN and related materials that appear to be contrary to this conventional wisdom. Indeed, highly efficient optoelectronic devices, both light-emitting diodes (LEDs) and laser diodes (LDs) have been fabricated in materials with defect densities as high as 1E10 cm-2. A number of unsupported misconceptions regarding the significance (and possible beneficial effects) of defects in these materials has arisen around such demonstrations and the commercialization of these devices. Many of these misconceptions can be addressed by quantitative study of the materials properties associated with such defects. Additionally, the presence of dislocations severely limits the process latitude in the production of such devices. Recently, there has been renewed interest in techniques related to dislocation reduction in GaN base materials, largely related to lateral overgrowth on patterned substrates. These have provided a unique opportunity to study the effects of defects in a controlled situation, and are driven by the requirement for improved mate-

rials properties in the materials. This will be discussed in the context of technology related to commercialization.

2:30 PM *Invited

GaN Lateral Epitaxial Overgrowth (LEO) on Silicon and Sapphire Substrates: *S. P. Denbaars*[1]; [1]University of California, Mats. Dept., Bldg. EII, Santa Barbara, CA 93110

Lateral epitaxial overgrowth (LEO) of low defect density GaN on Si(111) and Sapphire substrates is demonstrated. The mechanism of defect reduction is characterized using scanning electron microscopy, atomic force microscopy, transmission electron microscopy, x-ray diffraction, photoluminescence spectroscopy, and cathodoluminescence imaging. The <1_1 00>-oriented LEO GaN stripes grown on silicon substrates are shown to have similar structural properties as LEO GaN grown on GaN/Al2O3 substrates: the surface topography is characterized by continuous crystallographic steps rather than by steps terminated by screw-component threading dislocations; the density of threading dislocations is <106 cm-2; the LEO regions exhibit crystallographic tilt (0.7-4.7°) relative to the seed region. Devices fabricated on LEO materials shown improved characteristics, in particular a large reduction in leakage current under reverse bias is observed for p-n junction and UV photodetectors. For detectors fabricated on the "wing" region of the LEO a reverse-bias dark current of 10nA/cm2 is measured, in contrast to 300mA/cm2 for conventional dislocated GaN diodes. LEO diodes also exhibit a decrease in unwanted sub-band gap spectral response and improved signal-to-noise characteristics due to reduced dislocation densities. This work was supported by the Office of Naval Research through a contract supervised by Dr. C. Wood and made use of the MRL Central Facilities supported by the NSF under award DMR-9123048. HM acknowledges financial support from NSERC (Canada). PF acknowledges financial support from a National Defense Sci. and Eng. Graduate Fellowship provided by ONR.

3:00 PM *Invited

Effect of Native Point Defects on Nitride Materials and Devices: *Chris G. Van de Walle*[1]; [1]Xerox PARC, 3333 Coyote Hill Rd., Palo Alto, CA 94304 USA

Native point defects have always been assumed to play an important role in the properties of nitride semiconductors. Nitrogen vacancies were long considered to be the source of n-type conductivity; we now know that their concentration is too low to have any serious impact on doping of n-type material. The unintentional n-type conductivity is due to incorporation of impurities (mainly silicon and oxygen); the theoretical predictions for the behavior of nitrogen vacancies and donor impurities have been confirmed by experimental measurements based on secondary-ion mass spectroscopy (SIMS), variable temperature Hall effect, photoconductivity, etc. While nitrogen vacancies do not affect n-type conductivity, they do act as compensating centers in p-type material. The presence of hydrogen (abundantly available during MOCVD and HVPE growth) tends to suppress the formation of vacancies, but some degree of compensation is unavoidable. Complexes can also be formed consisting of a nitrogen vacancy with one hydrogen (the maximum number that can be accommodated in the vacancy). I will discuss how these complexes behave during the annealing process used to activate p-type GaN, and why they may be responsible for the observed shift in luminescence lines. I will also describe the role of nitrogen vacancies as metastable centers responsible for persistent photoconductivity, and for the commonly observed blue emission in p-type GaN. Understanding the behavior of point defects in GaN is important, but most nitride-based device structures mainly consist of AlGaN. Experimental results indicate that doping efficiencies in AlGaN are lower than in GaN, and it is important to assess the role of point defects in this behavior. Nitrogen vacancies turn out to be more easily formed in AlGaN than in GaN. Along with an increase of the ionization energy, this causes a decrease in the observed hole concentration. I will discuss whether acceptors other than Mg may allow higher levels of p-type doping. The theoretical work described here is based on first-principles calculations using density-functional theory and pseudopotentials. The focus on vacancies is justified by the finding that other types of point defects (self-interstitials and antisites) have very high formation energies and are unlikely to occur in nitride semiconductors. Gallium vacancies have been shown to be connected

with the commonly observed yellow luminescence, a topic that will be addressed if time permits. I gratefully acknowledge collaborations with J. Neugebauer and C. Stampfl, and the support of DARPA.

3:30 PM Break

3:50 PM *Invited

The Effect of Doping and Growth Stoichiometry on the Properties of Threading Dislocations in GaN: *Alan F. Wright*[1]; Kevin Leung[1]; [1]Sandia National Laboratories, Dept. 1113, MS 1415, P.O. Box 5800, Albuquerque, NM 87185-1415 USA

Gallium nitride films grown on sapphire substrates typically contain between 10^8 and 10^{10} threading dislocations per cm[2] due to the substantial film-substrate chemical and lattice mismatch. A surprising result, however, is that it is still possible to fabricate highly efficient light-emitting diodes and even laser diodes from material grown on sapphire substrates. This has prompted suggestions that dislocations in GaN do not produce defect levels lying in the forbidden gap and therefore do not act as efficient minority-carrier recombination sites. To investigate this possibility, we have examined the relaxed structure and formation energy of an edge dislocation in GaN using first-principles theoretical techniques. Filled and open core structures have been examined as well as structures having vacancies along the dislocation core. Formation energies for these structures are calculated both as a function of growth conditions (Ga- or N-rich) and Fermi level. In addition, we have examined charge accumulation that occurs at an edge dislocation when in the presence of n- and p-type dopants in the surrounding material, and the influence this charge accumulation has on formation energies and the Fermi level.

4:20 PM *Invited

Effects of Point Defects and Dislocations on Transport Properties of GaN: *David C. Look*[1]; [1]Wright State University, Semiconductor Research Center, Dayton, OH 45435

In most semiconductor materials, point defects (vacancies, interstitials, antisites, and small complexes of these entities) and line defects (mainly threading dislocations) seem to have little effect on the electrical tranport properties, i.e. their influence on the carrier concentration n (for an n-type sample) and mobility m is minimal. In GaN, on the other hand, it is difficult, if not impossible, to explain the electrical properties by impurities alone. Early workers suggested that a native donor, the N vacancy V_N, was responsible for the high values of n, sometimes approaching 10^{20} cm^{-3}. Later research has indicated that O_N or Si_{Ga} species probably determine n in many or most cases, but some results still cannot be explained by these impurities. Recently, temperature-dependent Hall-effect measurements, on electron-irradiated HVPE and MOCVD layers, have been used to show that V_N is indeed a shallow donor, with an activation energy E_a of about 65 meV (at the 10^{17} -cm-3 level), but that is not the typical residual shallow donor found in the "best" present-day GaN layers, which have E_a's closer to about 20 meV. However, V_N still may be dominant in some of the highly conductive bulk and epitaxial samples. Besides n, we must also consider mobility m, and here the acceptor concentration is the most important factor (in an n-type sample grown under Ga-rich conditions, and indeed positron annihilation experiments have identified a negatively-charged vacancy, probably V_{Ga}. However, again in the "best" present-day layers, SIMS measurements indicate that impurities, mainly C, can account for the measured acceptor concentrations. Thus, the relative influences of impurities and defects on the overall acceptor concentration is unclear at this point. With regard to dislocations, GaN grown on sapphire is a special case, because threading dislocation concentrations can approach 10^{10} - 10^{11} cm^{-2}. Theory shows that threading edge dislocations should act as negative line charges in n-type GaN, and that a concentration of 2 x 10^{10} cm^{-2} will reduce the 300-K mobility from about 700 to about 150 cm2/V-s in material with donor and acceptor concentrations in the low-10^{17} -cm-3 range. Thus, it is likely that high values of dislocations are responsible for low mobilities in such cases. This is perhaps the explanation for the fact that MBE GaN layers typically have lower mobilities than those grown by MOCVD and HVPE. Thickness, of course, also is important in the determination of mobility. In summary, both point defects and threading dislocations affect transport in GaN. We can quantitatively predict the effects for given concentrations of

each; however, the inverse process in much more difficult, because, among other things, impurity concentrations are not easy to determine accurately. Hopefully, theory and experiment will continue to make progress in this important area.

4:50 PM *Invited

Lateral and Pendeo-Epitaxial Overgrowth and Defect Reduction of GaN Films: *Robert F. Davis*[1]; O-H. Nam[1]; Thomas Gehrke[1]; Kevin J. Linthicum[1]; Tsvetanka S. Zheleva[1]; Pradeep Rajagopal[1]; Darren B. Thomson[1]; Chris A. Zorman[2]; Mehren Mehregany[2]; [1]North Carolina State University, Mats. Sci., Box 7907, Raleigh, NC 27695-7907 USA; [2]Case Western Reserve University, Elect., Systems and Comp. Eng. and Sci., Cleveland, OH 44106 USA

Conventional heteroepitaxial growth of GaN on low temperature GaN or AlN buffer layers previously deposited on Al2O3 and SiC substrates results in films containing a high dislocation density (108-1010 cm-2) due to the lattice mismatches between the buffer layer and the film and/or the buffer layer and the substrate. The objective of this research has been the significant reduction in dislocation density in GaN thin films via special methods of MOVPE growth. The lateral epitaxial overgrowth (LEO) of GaN stripes patterned in an SiO2 mask deposited on GaN film/AlN buffer layer/6H-SiC(0001) substrates was the initial method. The mask contained 3mm and 5mm wide stripe openings, spaced parallel at 3-40mm, and oriented along < > and < > in the GaN film. The deposited material grew vertically to the top of the mask and then both laterally over the mask and vertically until coalescence. The average RMS roughness of the LEO layers was 0.25 nm. This is similar to the values of the seed GaN films. Threading dislocations, originating from the GaN/AlN buffer layer interface, propagate to the top surface of the regrown GaN layer within the window regions of the mask. By contrast, there were no observable threading dislocations in the overgrown portions of the layer. The few dislocations observed formed parallel to (0001) plane via the extension of the vertical threading dislocations after a 90° bend in the regrown region. They did not subsequently propagate to the surface of the overgrown GaN layers. Recently we have pioneered a new process route to selective epitaxy of GaN and AlxGa1-xN layers, namely, pendeo-(from the Latin: to hang or be suspended) epitaxy (PE). This approach differs from LEO in that growth is forced to selectively begin on the sidewalls of a tailored microstructure comprised of forms previously etched into this seed layer. Continuation of the pendeo-epitaxial growth of GaN or the growth of the AlxGa1-xN layer until coalescence over and between these forms results in a complete layer of low defect-density GaN or AlxGa1-xN. This is accomplished in one (GaN), two (AlxGa1-xN) or multiple (multilayer heterostructure) re-growth steps. In summary, continuous GaN films having low dislocation densities have been achieved via LEO and PE techniques. This work was supported by the Office of Naval Research under contracts N00014-96-1-0765 (C. Wood, monitor) and N00014-98-1-0122 (J. Zolper, monitor).

5:20 PM *Invited

Characterization of Nitride Semiconductor Heterostructures and Laser Diodes: *D. P. Bour*[1]; M. Kneissl[1]; L. T. Romano[1]; C. G. Van deWalle[1]; J. Northrup[1]; N. M. Johnson[1]; [1]XEROX Palo Alto Research Center, Electr. Materials Laboratory, 3333 Coyote Hill Rd., Palo Alto, CA 94304

GaN and InGaN/AlGaN heterostructures have been deposited on A- and C-face sapphire substrates by MOCVD. We describe the structural and optoelectronic properties of these materials, and the performance characteristics of LEDs and laser diodes. Room-temperature, pulsed operation of a violet laser diode (l = 400 nm), containing 5 x 30 L $In_{0.1}Ga_{0.9}N$ quantum wells and $Al_{0.08}Ga0.92N$ cladding layers, was obtained, with threshold current density 5 kA/cm2. In this talk, nitride light-emitters will be discussed with an emphasis on how their performance characteristics are related to the nitride material properties.

Session F. Semiconductor Quantum Dots - Formation and Structure

Wednesday PM   Room: Multicultural Center Theatre
June 30, 1999   Location: University Center

Session Chairs: Ben V. Shanabrook, Naval Research Lab, Code 6870, Washington, DC USA; Craig Pryor, Pryor Consulting, Porterville USA

1:30 PM

Infrared Spectroscopy of Intraband Transition in Modulation Boron-doped GeSi Quantum Dot Superlattices: *Wen-Gang Wu*[1]; Yin-Sheng Tang[2]; [1]University of California-Los Angeles, Device Research Lab., Dept. of Elect. Eng., 56-125B EIV, P.O. Box 951594, Los Angeles, CA 90095-1594 USA; [2]University of California-Los Angeles, Device Research Lab., Dept. of Elect. Eng., 56-125B EIV, P.O. Box 951594, Los Angeles, CA 90095-1594 USA

Fourier transform and Raman scattering infrared spectroscopy of modulation boron-doped Ge/Si quantum dot superlattices is reported for the first time in this paper. The structures, which were grown on (001) oriented Si substrates by a solid source molecular beam epitaxy system, are composed mainly of a 30 period Ge/Si quantum dot multilayers, each with a thin undoped Ge dot layer sandwiched in between two 6 nm thick boron-doped Si spacer films. The structural properties of the superlattices and of the uncapped Ge dots grown on the surfaces of some samples were tested by cross-sectional transmission electron and atomic force microscopes, respectively. The testing indicates that the well-grown Ge quantum dots have a typical flat lens-like shape with a base dimension of around 42 nm and a height of around 4 nm and tend to be stacked on top of each other along the growth direction while their in-plane positions are random. The area density of the dots per layer should keep constant and its number is about 2x108 c m-2. The nonuniformity of the dot size is estimated to be +-10%. The periodicity of the structures is excellent in the growth direction. Through use of Fourier transform infrared and Raman scattering spectrometers, infrared absorption signals peaking in the mid-infrared range were observed. An infinite-barrier quantum box without considering exciton effects as well as dielectric screening is used to be the model of any of the Ge quantum dots. The calculated energies of the allowed hole states in the dot suggests that the mid-infrared response be attributed to heavy hole bound-to-bound intraband transitions in the Ge quantum dots. The coupling among the corresponding heavy hole quasi-bound states in different Ge dots along the growth direction is taken into the analysis account. Also, the polarization dependence features of the absorption spectra were investigated. It is found that the absorption intensity decreases as the polarization angle of the incidence infrared light increases. With regard to the flatten lens-like Ge quantum dots sandwiched in between two boron-doped Si spacer films, the quantum confinement become strong along the growth direction but weak in the lateral directions. The fact that the infrared absorption is strongly polarized along the growth axis of the samples implies that the polarization selection rule of the intraband transitions within the valence band of the flat lens-like Ge quantum dots is similar to the polarization selection rule of intersubband transitions in the valence band of Ge/Si-based quantum wells. This study demonstrates the application potential of this kind of Ge/Si quantum dot superlattices for developing mid-infrared photodetectors.

1:50 PM

Study of Phonons in Self-Organized Multiple Ge Quantum Dots: *Jianlin Liu*[1]; Yinsheng Tang[1]; Kang L. Wang[1]; [1]University of California at Los Angeles, Dept. of Elect. Eng., Device Research Laboratory, Los Angeles, CA 90095-1594

Self-organized Ge quantum dots by the Stranski-Krastanov growth mode have attracted much interest, because these quantum dots are expected to show very large optical nonlinearity and offer the potential for fabricating novel optical devices. To date, much experimental progress on the photoluminence and Fourier transform infrared spectroscopy has been made to study the size-quantized electronic states in these dots. However, little work has been done on the investigation of the vibrational states of the self-organized Ge quantum dots embedded in Si matrices even though information on phonons is indispensable for understanding electron-phonon interactions in the dots. In this presentation, Raman measurements are used to study phonons in multiple Ge quantum dots. A series of multiple Ge quantum dot samples with different dot sizes are grown using solid source molecular beam epitaxy (MBE). The shapes and sizes of the dots are characterized by means of atomic force microscopy (AFM) and transmission electron microscopy (TEM). Raman scattering is carried out at room-temperature in a back-scattering configuration. All spectra are excited by 514-nm line and recorded by a CCD camera. From the Raman lines observed in the low frequency range (below 1000 cm-1), the information for acoustic, optic and interface phonons is extracted. The size dependence of the Raman line shows phonon confinement and strain effects in the dots. In the high frequency range (above 1000 cm-1), we perform polarization-dependent Raman measurements. Raman peaks originating from the inter-sub-level transitions between the first and second quantized hole states in the dots are observed.

2:10 PM

Raman Spectroscopy of the Topology of the InAs/GaAs Self-Assembled Quantum Dots: Yuri Alexander Pusep[1]; [1]Federal University of Sao Carlos, DF, Via Washington Luis, km 235, Sao Carlos, Sao Paulo 13565-905 Brasil

In order to study the topology of the InAs/GaAs quantum dots we measured the resonance Raman scattering of the interface vibrational modes localized near the tips of the dots. The contribution of these modes to the Raman scattering, being proportional to the density of the dots, has been shown to appear at the resonance with electron excitations confined in the InAs dots [1]. Thus, the Raman lines associated with such interface modes can serve as indicators of the presence of the quantum dots. By comparison of the Raman spectra measured in the samples with and without the GaAs capping layer it was found that the dots are formed on both sides of the wetting layer. This result testifies to the formation of the dot structure under the wetting layer as well as on it, which agrees with the recent observations showing that the dots are rather embedded within the wetting layer [2,3]. In addition, in the multilayered systems of the InAs/GaAs quantum dots, the evidence of the coalescence of the dots in neighbour layers separated by the distance smaller than 25 monolayers was obtained. [1] Yu.A.Pusep, G.Zanelatto, S,W. da Silva, J.C.Galzerani, P.P.Gonzalez-Borrero, A.I.Toropov, P.Basmaji, Phys.Rev. B58, R1770 (1998) [2] B.Legrand, B.Grandidier, J.P.Nys, D.Stievenard, J.M.Gerard, and V.Thierry-Mieg, Appl.Phys.Lett., 73, 96 (1998) [3] P.D.Sieveras, S.Malik, G.McPherson, D.Childs, C.Roberts, R.Murray, B.A.Joyce, and H.Davock, Phys.Rev. B58, 10127 (1998)

2:30 PM

Microscopic Transient Photoluminescence of Site-Controlled InAs Dots: *Tetsuya Nishimura*[1]; Tomonori Ishikawa[1]; Shigeru Kohmoto[1]; Kiyoshi Asakawa[1]; Osamu Wada[1]; [1]The Femtosecond Technology Research Association, 5-5 Tokodai, Tsukuba, Ibaraki 300-2635 Japan

Capability of controlling the location, size, density and mutual coupling of quantum dots are desired for the expertise acquisition of nano-structural physics and the application to novel opto-electronic devices. We reported the achievement of site-controlled InAs quantum dots using in situ electron-beam process to form holes for growth sites [1]. The use of submicron site-control holes produces series of quantum dot arrays having high spatial density. However, there has been very few studies on optical characterization of quantum dots with spatial and

temporal resolution especially at wavelength longer than 1 micron. This paper describes the first observation of transient photoluminescence (PL) of site-controlled InAs dots by using novel microscopic exciting and probing system. The size of excitation beam was about 2 microns without using surface mask on the sample set in a cryostat, and the time and energy resolutions were several ps and below 1 meV, respectively. Site-controlled InAs dots were grown selectively inside the holes aligned at 1 micron pitch, and dots were scarcely found outside the holes. The total number of quantum dots under observation was estimated to be several tens, because approximately five sites were included in the excitation beam spot and nearly ten dots were observed in each site in AFM images. The local density of quantum dots in one site was evaluated to be over 10^{11} cm^{-2}, much larger than usually observed for conventional self-assembled Stranski-Krastanov (SK) dots. The excitation was carried out by 160 fs-wide pulses with 80 MHz repetition rate at the energy of 1.64 eV and the density of 30 W/cm^2. The PL spectrum of quantum dots was observed as a single peak at 1.25 eV with the FWHM of 80 meV, similar for conventional SK dots. The PL decay times at different emission energies showed considerable variation over twice difference. In contrast, the decay times in the reference SK dots, which are uniformly dispersed in lateral dimension at about 10^{10} cm^{-2}, were almost constant at 700 ps throughout the PL spectrum. For isolated dots, the PL decay time exhibits the individual recombination lifetime, and this is independent of the emission energy. In dense dots, however, an excited state of coupled dots relaxes to a local minimum through tunneling, and prolonged decay time is observed at lower emission energy [2]. Thus, microscopic PL decay was used to characterize the coupling among quantum dots. The result reported indicates the capability of controlling the dot density in the present site-controlled growth technique. This work was performed under the management of The Femtosecond Technology Research Association (FESTA) supported by New Energy and Industrial Technology Development Organization (NEDO). [1] T. Ishikawa et al., Appl. Phys. Lett. 73 (1998) 1712. [2] A. Tackeuchi et al., Jpn. J. Appl. Phys. 34 (1995) L1439.

2:50 PM

Optical Properties of InAs/InP Self-Assembled Quantum Dots Grown by Metalorganic Chemical Vapor Deposition: *Euijoon Yoon*[1]; Youngboo Moon[1]; Tae-Wan Lee[1]; Heedon Hwang[1]; Sukho Yoon[1]; Young Dong Kim[2]; Uk Hyun Lee[3]; Donghan Lee[3]; Hong-Seung Kim[4]; Jeong Yong Lee[4]; [1]Seoul National University, School of Mats. Sci. & Eng., Rm. 32-203, Seoul 151-742 Korea; [2]Kyung Hee University, Dept. of Phys., Seoul Korea; [3]Chungnam National University, Dept. of Phys., Taejon Korea; [4]Korea Advanced Institute of Sci. & Technology, Dept. of Mats. Sci. & Eng., Taejon Korea

The InAs self-assembled quantum dot (SAQD) on InP is a promising candidate for the optoelectronic devices operating at 1.55 ㎜ for optical communication. Nevertheless, reports on InAs/InP SAQDs are quite limited in number, in part due to the complexity of the dot formation mechanism associated with the As/P exchange reaction. Effects of MOCVD process parameters such as temperature, InAs coverage, and growth interruption on InAs SAQDs have been reported. However, the detailed role of the growth interruption and the As/P exchange reaction in the InAs SAQD formation is not yet clearly understood. We previously reported the growth of high-density (4.5 x 10^{10} /cm^2) InAs SAQDs on InP by MOCVD [1]. Effects of the As/P exchange reaction at various temperatures and V/III ratios on the formation of SAQDs were discussed in detail. It was also found that the "excess InAs" formation was very critical in the InAs/InP SAQD formation. In this study, we present the optical properties of the InAs/InP SAQDs prepared by MOCVD. Photoluminescence (PL) measurements were carried out at various temperatures (21-300 K) and various pump power densities (0.24 - 24 W/cm^2). High-resolution transmission electron microscope (HRTEM) images showed clear formation of quantum dots without extended defects. The InAs/InP SAQD sample capped with InP without growth interruption showed a few PL peaks other than a quantum dot peak at 0.820 eV, presumably from the thickness fluctuation of the wetting layer before the complete evolution to quantum dots. However, the InAs/InP SAQD sample with 30 sec growth interruption before InP capping showed a PL peak at 0.776 eV at 21 K. The peak position shifted slightly to a lower energy of 0.742 eV at 300

K. The full width at half maximum (FWHM) of the peak, however, did not change much with temperature: 116 meV at 21 K and 115 meV at 300 K. Also, the integrated intensity of the peak from the quantum dot remained relatively unchanged with temperature. The InAs SAQDs grown on 2 nm InGaAs/InP showed the similar PL behavior except the fact that the PL peak position at 21 K was at 0.807 eV. The changes in the PL peak positions were believed to result from the changes in barrier height as well as the changes in the shape of the dots with the InGaAs buffer layer [2]. The dots grown directly on InP was dome-shaped, whereas those grown on InGaAs buffer were faceted pyramids with parallelogram bases. In the latter sample, a peak from InGaAs quantum well was also observed, however, it disappeared at temperatures higher than 80 K. The SAQD PL peak did not change its position even though the pump power density varied by two orders of magnitude from 0.24 to 24 W/cm², strongly suggesting that the InAs/InP SAQD is very promising for the future devices for long-wavelength optical communication. [1] S. Yoon, Y. Moon, T.-W. Lee, E. Yoon, and Y.D. Kim, "Effects of As/P exchange reaction on the formation of InAs/InP quantum dots", Appl. Phys. Lett., accepted for publication. [2] S. Yoon, Y. Moon, T.-W. Lee, E. Yoon, and Y.D. Kim, "Shape change of InAs self-assembled quantum dots", Paper #B2.5, 1998 Fall Meeting of Mat. Res. Soc., Nov. 30 - Dec. 4, 1998, Boston, MA.

3:10 PM Break

3:30 PM
Fluorescence Intermittency and Quantum Efficiency of Individual Porous Silicon Nanoparticles: *Michael D. Mason*[1]; Grace M. Credo[1]; Steven K. Buratto[1]; [2]University of California-Santa Barbara, Dept. of Chem., Goleta, CA 93106 USA

We use a combination of scanning force microscopy, laser scanning confocal microscopy, and single particle spectroscopy to investigate the optical properties of single porous Si nanoparticles. Our experiments have shown a variety of phenomena not previously observed in the emission from porous Si including a distribution of emission wavelengths, dynamic spectral drift, resolved vibronic structure, discrete jumps in intensity, luminescence intermittency and irreversible photobleaching. We will present our recent findings regarding the fluorescence intermittency and near unity quantum efficiency of individual porous Si nanoparticles as well as our working model of a statistical distribution of high QE quantum-confined Si chromophores.

3:50 PM
Origin of Size Distribution in ZnSe Self-Organized Quantum Dots Grown on ZnS layers: *Takehiko Tawara*[1]; Satoru Tanaka[1]; Hidekazu Kumano[1]; Ikuo Suemune[1]; [1]Hokkaido University, Research Institute for Electr. Sci., Kita-12, Nishi-6, Kita-ku, Sapporo, Hokkaido 060-0812 Japan

In recent years, self-organized quantum dots (QDs) have attracted much attention to the application of new optical devices such as QD lasers. However, the size inhomogeneity of the self-organized dots is usually broadened and reduces the optical gain. From this view point, it is necessary to understand the main factors which determine the size distribution. In self-organized QDs, it has been attributed to the strain in QDs induced by the mismatch with an underneath layer. [1] On the other hand, Ebiko et al. reported that the dot size distributions of the InAs QDs are independent of the strain and are well reproduced by the same scaling function regardless of the QD densities. [2] In this paper, the main factors determining the size distribution in ZnSe self-organized QDs grown on ZnS layers are studied. All of the samples were grown by metalorganic vapor phase epitaxy at 350℃. The ZnSe QDs were grown by depositing about 3-monolayer-thick ZnSe after the growth of ZnS underneath layer. The sizes of the individual ZnSe QDs were measured by an atomic force microscope. To understand the size determining process in our ZnSe QDs, the scaling characterization using standard rate equation theory based on deposition, diffusion and aggregation rates considering the smallest stable island size [3] was attempted. In the case of the InAs QDs, its size distribution has a critical size and the smallest stable island size was like polymers, i.e. dimers, trimers and so on. [2] The scaling of the ZnSe QDs size distribution was also possible, but it did not show any critical QDs sizes. In this case, the smallest stable islands contributed to the size distribution

will be monomers. This situation corresponds to the spontaneous nucleation or freezing of monomers. Therefore, from the viewpoint of the scaling function, it was clear that the main factor determining the size distribution of the ZnSe QDs is different from the InAs QDs case. The influence of the size distribution on the surface roughness of the ZnS underneath layer was also examined. When the ZnSe QDs were grown on the ZnS surfaces which have the various surface roughness, it was revealed that the size distribution and the average size of ZnSe QDs were reduced with the decrease of the ZnS surface roughness. These results indicate that besides the strain the fluctuation of the surface potential seriously contributes to the size distribution of self-organized QDs. References [1] A. -L. Barabasi: Appl. Phys. Lett. 70 (1997) 2565. [2] Y. Ebiko, S. Muto, D. Suzuki, K. Shiramine, T. Haga, Y. Nakata, and N. Yokoyama: Phys. Rev. Lett. 80 (1998) 2650. [3] J. G. Amar, and F. Family: Phys. Rev. Lett. 74 (1995) 2066.

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Structural Studies of Stacked InAs Quantum Dots in a Silicon Matrix Grown by MBE: N. D. Zakharov[1]; *Peter Werner*[1]; Victor M. Ustinov[2]; George E. Cirlin[2]; O. V. Smolski[2]; D. V. Denisov[2]; P. S. Kop'ev[1]; Zh. I. Alferov[2]; N. N. Ledentsov[2]; Robert Heitz[3]; Dieter Bimberg[3]; [1]MPI of Microstructure Physics, Halle (Saale) D - 06120 Germany; [2]A.F. Ioffe Physical-Technical Institute, St. Petersburg Russia; [3]Technical University of Berlin, Berlin D-10623 Germany

There is a great interest in combination of silicon, being a key material of microelectronic technology, with III-V compound semiconductors being the key material of modern optoelectronics. It was recently proposed /1/ that the III-V quantum dots (QD's) can be coherently introduced in a Si matrix. The InAs-Si system is very advantageous in view of its band alignment. If such InAs islands have a size of several nanometers, discrete confined states can be formed. However, due to the large lattice mismatch characteristic to the InAs-Si system of about 10%, the growth can proceed via formation of mesoscopic dislocated clusters rather than via formation of strained nanoscale islands which can be usually realized via Stranski-Krastanow growth on GaAs substrates. Molecular beam epitaxy (MBE) was applied to fabricate coherent InAs islands on a (001) Si substrate, afterwards epitaxially covered by silicon layers. The influence of growth parameters, such as substrate temperature (in our experiments: 400-620°C), the InAs growth rate, the average thickness of the insertion and the As pressure during growth have been investigated. Scanning tunneling microscopy (STM) studies demonstrated that small InAs quantum dots (QDs) can be, indeed, formed on a Si (100) surface, and, after overgrowth with Si, these QD's demonstrate intense and broad luminescence line at about 1.3 microm at 10 K /2/. Despite of the high importance of these spectroscopic results no direct proof of the coherent nature of the InAs insertions in a silicon matrix was given. The present work describes the results of structural characterization of nm-scale InAs QD's incorporated in a Si matrix. High-resolution electron microscopy has been applied to prove the coherent nature of the InAs inclusions. Experimental micrographs were additionally compared with computer simulated images of crystallographic models. We observed that the quality of the grown structures severely depends on the substrate temperature, growth sequence, and geometrical parameters of the heterostructure. In addition to the STM results, one can also conclude that the Si crystal lattice can only adapt a limited volume of the deposited InAs in a form of coherent clusters; excess of InAs is accumulated in large, dislocated precipitates. The growth phenomena observed is discussed in view of the interplay of thermodynamic aspects and kinetic pathways of the growth process. /1/ N.N. Ledentsov, Proceedings of the 23rd International Conference on the Physics of Semiconductors, Berlin, Germany, July 21-26, 1996, Ed. by M. Scheffler and R. Zimmermann (World Scientific, Singapoure, 1996), v. 1, p. 19./2/ G.E. Cirlin, et al., Semicond. Sci. and Technol. 13, 1262 (1998).

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In-Situ Self-Organization of Two- and Three-Dimensional High-Density InAs Quantum Wire Arrays on (100) InP: *Hanxuan Li*[1]; Theda Daniels-Race[1]; Zhanguo Wang[2]; [1]Duke University, Dept. of Elect. & Comp. Eng., Durham, NC 27708-0291 USA; [2]Institute of Semiconductors, Chinese Academy of Sciences, Laboratory of Semiconductor Mats. Sci., Beijing 100083 P. R. China

The continued minimization of electronic devices continues to lead us into a realm of nanostructures. Although InGaAs quantum wires (QWRs) on vicinal InP (100) substrates have been demonstrated[1], and reports are available on the realization of $In_xAl_{1-x}As$ QWRs by depositing InAs/AlAs short-period supperlattices on on-axis (100) InP[2,3], there are no results available regarding the formation of InAs QWRs on InP substrates. In this work, we report the observation of InAs wire formation on (100) InP by molecular beam epitaxy. By stacking the wires into multilayers, highly correlated three-dimensional (3D) wire arrays are realized. The samples were grown on semi-insulating (100) InP substrates by a solid-source MBE system. The heterostructures consist of a 200-nm $Al_{0.48}In_{0.52}As$ buffer layer, an active region, and a 50-nm $Al_{0.48}In_{0.52}As$ cap layer. For the single-layer samples, the InAs active layer was varied from 1.5~10ML. For the multilayer samples, 20-, 10-, and 5-nm $Al_{0.48}In_{0.52}As$ spacer layer were grown after each InAs deposition. The growth rates of $Al_{0.48}In_{0.52}As$ and InAs were 0.7 and 0.2 mm/hr, respectively. No growth interruptions were introduced during the growth process. The samples were characterized by in situ reflection high-energy electron diffraction (RHEED) measurements, ex situ atomic force microscopy (AFM), transmission electron microscopy (TEM) and photoluminescence (PL) to examine and verify the existence of quantum wires. The surfaces of the single-layer samples are dominated by quasi-periodic quantum wires which are coherently strained to the substrates. It is confirmed from the diffraction pattern that the wires are elongated along the <-110> direction, while the height undulation is manifest in <110>. In the 3~6 ML regime, the surface structures appear extremely stable, the wires grow, but retain their essential shape. One distinct dimensional changes of the wires is that the lateral size, height, and periodicity of the wires increases significantly with deposition. At 6 ML, the average spacing, lateral width and height of the wire structures are 14nm, 10nm and 3nm, respectively. The linear wire density, therefore, is so high (~70 wires/ mm) that neighboring wires almost touch each other in their base regions. The striking features of the multilayer wire arrays is that the wires of the upper layer are not reproduced directly above the buried wires but approximately between two neighboring ones. Detailed cross-sectional TEM investigations reveal the existence of a wire correlation that is not parallel but is along crystallographical directions inclined by an angle q to the growth direction (100). This picture is in marked contrast to the widely accepted theory of vertical alignment of quantum dots, which is qualitatively explained by the strain-anisotropy-induced oblique reproduction. For our material system, the ordering mechanism is so efficient that a nearly perfect hexagonal packing of wires was observed in the cross-section. When spacer thickness d is varied by a factor of 4, the general picture of spatial alignment is not affected. There is a 50% reduction in the photoluminescence (PL) linewidth between the case of a single-layer sample (120meV) and the case of a multilayer sample with 5 nm spacer layer (80meV). At the same time, the PL peak of the wires is shifted by 60 meV to lower energy which is ascribed to the electrical coupling effects among the high-density wires. This work has been partially supported by the National Sci. Foundation and the Dept. of Energy. 1. M. Brasil, A. Bernussi, A. M. Cotta, M. Marquezini Appl. Phys. Lett. 65, 857(1994) 2. Shinjiroh Hara, Junichi Motohisa, and Takashi Fukui, J.Crystal Growth 170, 579(1997) 3. A. G. Norman, S. P. Ahrenkiel, H. Moutinho, M. M. Al-Jassim, Appl. Phys. Lett. 73, 1844(1998)

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Session G. Epitaxy for Devices

Wednesday PM   Room: State Street
June 30, 1999   Location: University Center

Session Chairs: Ray Tsui, Motorola Labs, Tempe, AZ USA; Mike Tischler, Epitronics Corporation, Mesa USA

1:30 PM
Tellurium Memory Effects on OMVPE-Grown In0.3Ga0.7As-0.997N0.003/GaAs Laser Diodes: *Nein-Yi Li*[1]; Chris Hains[1]; Jun Lu[1]; Kai Yang[1]; Julian Cheng[1]; [1]University of New Mexico, Center for High Technology Materials, 1313 Goddard Ave. SE, Albuquerque, NM 87106 USA

Recently, a new semiconductor alloy, $InxGa1-xAs1-yNy$, which can be lattice-matched or strained to a GaAs substrate, has been extensively studied by molecular beam epitaxy (MBE) and organometallic vapor phase epitaxy (OMVPE) since it has been shown a great potential to realize long-wavelength edge emitting laser diodes and vertical-cavity surface emitting laser diodes lasing in the 1.15 to 1.30 ym regime with high-temperature performance for the future low-cost and high-capacity optical data links. Among these studies, silicon (Si) has been widely used as the n-type dopant, and its doping effects on optical properties of $InxGa1-xAs1-yNy$ quantum wells (QWs) is believed to be negligible. In this study, tellurium (Te) is employed as the n-type dopant due to its lower diffusion coefficient in GaAs, about two orders of magnitude lower than Si at 1000¢XC2. However, Te doping effects on optical properties of OMVPE-grown In0.3Ga0.7As0.997N0.003/GaAs QWs has not been reported yet. Therefore, in this study, photoluminescence (PL), secondary ion mass spectroscopy (SIMS), and light-current (L-I) characteristics were analyzed to evaluate optical qualities of 1.17 ym In0.3Ga0.7As0.997N0.003 laser diodes. The In0.3Ga0.7As0.997N0.0-07 laser diodes were grown at 535¢XC by OMVPE using dimethylhydrazine, diethyltellurium (DETe), and carbontetrachloride as the N, Te, and C precursors. Test samples with different growth procedures were employed to investigate the effects of Te dopant on optical properties of QWs. A 2000A-thick undoped or Te-doped (n=2x1018 cm-3) GaAs buffer layer was grown first on a (100) n+-GaAs substrate, followed by the growth of a 1400A-thick undoped GaAs waveguide layer, three In0.3Ga0.7As0.997N0.003 (70A)/GaAs (100A) QWs, and a 500A-thick GaAs cap layer. For samples grown on an u-doped GaAs buffer layer without any in-situ or ex-situ annealing, strong room-temperature PL at 1.17 ym with a full width at half maximum of 33 meV can be routinely obtained. However, for samples grown on a GaAs:Te buffer layer without or with a five-minute growth interruption show no or very weak room-temperature PL, respectively. SIMS results show that ~ 0.3-2x1020 cm-3 Te atoms exist in QWs, possibly attributed to the desorption of DETe from the stainless tube walls, the quartz reactor walls, or the graphite susceptor during the low temperature growth of QWs since Te has a tendency to incorporate at lower growth temperatures. From the L-I characteristics of 1.17-1.20 ym In0.3Ga0.7As0.997N0.003/GaAs laser diodes, we found for the first time that optical properties of In0.3Ga0.7As0.997N0.003/GaAs QWs were significantly deteriorated due to this unintentional Te incorporation in QWs, resulting in a higher threshold current density (Jth) of 6.0 KA/cm2. To circumvent the Te memory effect, in-situ cleaning quartz reactor and susceptor with hydrogen chloride at 830¢XC, followed by the regrowth of QWs and p-cladding layers were employed. A Jth of 1.2 KA/cm2 has been successfully demonstrated, and, to our best knowledge, it is the lowest among the 1.17-1.20 ym InxGa1-xAs1-yNy laser diodes grown by MBE or OMVPE. In summary, we have successfully improved optical performance of In0.3Ga0.7-As0.997N0.003/GaAs laser diodes by using in-situ etching and OMVPE regrowth techniques to eliminate Te carry-over in the QWs. Further characterizations and details on laser diodes will be presented.

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Investigation of p-type GaInNAs for Heterojunction Bipolar Transistor Base Layers: *Huoping Xin*[1]; Charles W. Tu[1]; Peter M. Asbeck[1]; Rebecca J. Welty[1]; [1]University of California at San Diego, Dept. of Elect. and Comp. Eng., 9500 Gilman Dr., La Jolla, CA 92093-0407 USA

A low-bandgap material for the base of a heterojunction bipolar transistor (HBT) is desirable to lower the emitter-base voltage V_{be} and decrease the turn-on voltage for low-power operation. GaInAs, pseudomorphically grown on the GaAs substrates, has been demonstrated as a base layer for GaAs-based HBTs. Pseudomorphic growth, however, restricts the range of In composition. Moreover, the resulting strain tends to lower the benefit from reduced bandgap in the alloy. Therefore, we propose a novel material GaInNAs as a base layer. Nitrogen incorporation in GaInAs lowers the band gap due to large bandgap bowing and reduces the net strain due to small atomic size of nitrogen. In this paper, we report the gas-source MBE growth and characterization of p-type $Ga_{0.892}In_{0.108}N_xAs_{1-x}$ (1100 Å) layers on semiinsulating GaAs substrates. The active nitrogen species are generated from a RF plasma nitrogen radical beam source. Rapid thermal annealing is also performed on the samples to improve their quality. The samples are characterized by high-resolution X-ray rocking curves (XRCs), photoluminescence (PL) and Hall measurements. XRCs show that the peaks of GaInNAs shift closer to the GaAs substrate peak with increasing N concentration, indicating reduced strain. Dynamical theory simulations are used to determine the In and N concentration, which are 0.108 and 0 ~ 0.024, respectively. After RTA at 700°C for 10 seconds, the $Ga_{0.892}In_{0.108}As$ sample suffers from strain-relaxation due to the large lattice-mismatch, but N-containing samples remain pseudomorphically strained, suggesting better thermal stability. For 700° C-annealed samples, the room-temperature PL wavelength red-shifts from 0.988 to 1.276 micron with increasing N concentration from 0 to 0.024 due to the large bandgap bowing. Hall measurements show that with N incorporation, the carrier concentration is decreased by one order of magnitude and Hall mobility also decreases. After RTA, however, the carrier concentration of N-containing samples is increased to the same level as that of GaInAs and the Hall mobility also increases. The product of carrier concentration and Hall mobility is about half as that of GaInAs sample. These results suggest GaInNAs is a promising advanced material for the base layer of HBTs. The lower bandgap compared to GaAs could decrease the turn-on voltage V_{be} by as much as 0.4V. Since much of the bandgap reduction is believed to correspond to a change in conduction band energy, a design in which conduction band barriers are eliminated with grading and doping dipoles will be required.* This work was partially supported by Rockwell International and UC Micro.

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Growth and Characterization of Long Wavelength (1 Micron) GaInAsN Photo-Detectors using Gas Source Molecular Beam Epitaxy: *Sudhir G. Subramanya*[1]; Joachim Kruger[1]; Piotr Perlin[1]; Eicke R. Weber[1]; Dan E. Mars[2]; Chris Kocot[2]; Ying-Lan Chang[2]; [1]University of California at Berkeley, Mats. Sci. and Min. Eng., 161M, 211-225 Cory Hall #1772, Berkeley, CA 94720-1772 USA; [2]Hewlett Packard Laboratories, 3500 Deer Creek Rd., B26M-7, Palo Alto, CA 94304 USA

Optical communication has created a strong interest in light emitters and detectors in the infra-red wavelength range. However, this wavelength range is not achievable with GaAs based semiconductor technology due to fundamental limitations such as lattice mismatch of InGaAs/GaAs hetero-structures. Therefore, InGaAs-based hetero-structures have to be grown on InP substrates. Devices fabricated using InGaAs/InP technology suffer from poor temperature characteristics. Also, InP substrates are expensive, fragile and of poorer quality. Recently, some progress has been made on GaInAsN/GaAs heterostructures for lasers [1]. The addition of small amounts of N to GaAs causes a large decrease in the band-gap. This also decreases the lattice constant, which can be compensated by addition of Indium so as to adjust it to the GaAs lattice constant. This enables fabrication of detectors on a transparent substrate, which allows for the radiation detection from the device backside. In this work, for the first time, GaInAsN layers were used to make photo-detectors in the 1 micron long wavelength range. GaAsN and GaInAsN layers were grown using gas source molecular beam epit-

axy. The effect of the substrate temperature, the power to the electron cyclotron resonance (ECR) plasma source, the rate of growth, and As-flux on the GaAsN material properties were studied. The N concentration in GaAsN was determined by x-ray diffraction and secondary ion mass spectroscopy to be in the range of 0 to < 2%. X-ray diffraction results indicated the incorporation of N in GaAs increases with the ECR power to the N-source and with slower growth rate, but was not affected by the substrate temperature. Low temperature photoluminescence spectroscopy results showed a drastic narrowing of the bandgap with N incorporation. The optical quality of the layers improved by 2 orders of magnitude with increased growth temperature. Based on the results of the detailed materials characterization, optimized p-GaAs/i-GaInAsN/n-GaAs/SI-GaAs structures were grown for 1 micron photo-detectors. The device parameters of the prototype devices will be compared with the results of the device simulation. [1] M. Kondow, K. Uomi, A. Niwa, T. Kitatani, S. Watahiki, and Y. Yazawa, Jpn. J. Appl. Phys., 35, 1273 (1996).

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InGaAsN for High Efficiency Solar Cells Grown by Metalorganic Chemical Vapor Deposition: *Andrew A. Allerman*[1]; Steven R. Kurtz[1]; Eric D. Jones[1]; James M. Gee[1]; Rob M. Sieg[1]; [1]Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185 USA

InGaAsN alloys are being developed for high efficiency multi-junction tandem solar cells for space power systems. Models indicate that record efficiencies (» 38-40%) would be obtained for tandem cells where a 1.05eV bandgap cell is added in series to proven InGaP-GaAs tandem structures. The $In_xGa_{1-x}As_{1-y}N_y$ alloy system appears ideal for this application. Bandgaps less than 1.0eV are obtained for $In_xGa_{1-x}As_{1-y}N_y$ alloys with minimal N concentrations (y » 0.02). $In_xGa_{1-x}As_{1-y}N_y$ films were grown using trimethylindium (TMIn), trimethylgallium (TMG), 100% arsine and dimethylhydrazine (DMHy). N-type material was achieved using silicon tetrachloride (SiCl4). Carbon tetrachloride (CCl4) and dimethylzinc (DMZn) were used to dope films p-type. High DMHy/V ratios (0.94 - 0.98) were required to incorporate nitrogen. The V/III ratio ranged between 50 to 100 and the growth rate between 6 and 10Å/sec. N-type material was doped using SiCl4 since Si2H6 and DETe proved ineffective at 600°C. Electron concentrations to 5e17 were achieved but alloy composition was affected at the higher doping levels as measured by x-ray diffraction. Following thermal annealing, the hole concentration increased in p-type material and the electron concentration decreased in n-type material or became p-type. Other n-type dopants will be discussed. A significant increase in photoluminescence intensity was observed from films following a post-growth thermal anneal. The photoluminescence intensity was a maximum for samples annealed for either 700°C for 2 minutes or 650°C for 30 minutes. Without annealing, little band edge luminescence was observed at 300K and only a broad, low energy band was present. A solar cell was constructed with a 1.0 μm thick, n-type (2 x 1017 cm-3, Si doped) In0.07Ga0.93As0.98N0.02 emitter grown on a 1.0 μm thick, p-type (4 x 1016 cm-3, background doped) base. An AlGaAs window and a GaAs back surface reflector were incorporated. The photoresponse extended out to the band-edge of the InGaAsN at 1.2 μm. Peak internal quantum efficiencies of >70% were obtained for the annealed cell. Comparing the annealed and as-grown cells, annealing improved the quantum efficiency by roughly a factor of 5. Comparing the performance of our thick n-type emitter solar cell with thin n-type emitter cells and other alternative designs, we found that negligible electron diffusion is occurring in the 1.0 eV p-type material (annealed or as-grown). To date, high quantum efficiencies have only been obtained with cell designs utilizing hole diffusion in n-type material. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Dept. of Energy under contract DE-AC04-94AL85000. Additional funding was provided by Air Force Research Laboratory.

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AlGaAs and InGaAs-Based Light Emitters on Si via Relaxed Graded GeSi Buffer Layers: *Michael E. Groenert*[1]; Vicky K. Yang[1]; Eugene A. Fitzgerald[1]; [1]Massachusetts Institute of Technology, Dept. of Mats. Sci. and Eng., Rm. 13-4025, 77 Massachusetts Ave., Cambridge, MA 02139 USA

The promises inherent in merging conventional silicon-based IC technology with the direct-gap optoelectronic capabilities of III-V semiconductor technology have inspired many different strategies for growing GaAs-based devices on silicon substrates. Minority carrier devices such as laser diodes, and high-aluminum content structures are the most sensitive to defects resulting from the mismatched GaAs/Si heterojunction. Continuing work in this research group with relaxed graded buffer layers of Ge_xSi_{1-x} grown on silicon wafers have created device-quality substrates upon which GaAs-based light-emitting and laser diode structures can be grown and evaluated. $Al_xGa_{1-x}As$ visible light emitting diodes have been grown on graded Ge_xSi_{1-x} substrates with organometallic chemical vapor deposition (OMCVD), and these devices have been characterized and compared with identical structures grown on standard GaAs substrates. Side-emitting double-heterostructure devices were fabricated with $Al_{0.41}Ga_{0.59}As$ cladding layers and an $Al_{0.2}Ga_{0.8}As$ active region luminescing at 740nm. Turn-on voltages of 1.5V and series resistances on the order of 10-4 W for the AlGaAs on GeSi diodes were measured, and similar values were recorded for the devices grown on GaAs. Electron-beam induced current (EBIC) images of both devices showed threading dislocation densities of approximately 4×10^6 cm^{-2} for the devices grown on Ge_xSi_{1-x}, and much lower densities ($< 10^{-4}$ cm^{-2}) in the devices grown on GaAs. Despite the differences in threading densities, both devices showed comparable luminescence characteristics, with external quantum efficiencies slightly more than an order of magnitude apart. $In_xGa_{1-x}As$/GaAs quantum well diodes have been shown to be exceptionally resistant to dislocation-induced failures under a wide range of operating conditions. Operating lifetimes for $In_{0.2}Ga_{0.8}As$ strained quantum well lasers on GaAs substrates longer than 20,000 hours have been reported (compared to 8000-hour average lifetimes reported in AlGaAs/GaAs QW lasers).[1] $In_xGa_{1-x}As$/GaAs quantum well diode structures on both GaAs and GeSi substrates have been grown and characterized. Pulsed laser operation at 991 nm with a threshold current of 105 mA was achieved with the devices grown on GaAs substrates, and IV and PL measurements on diodes grown on both GaAs and GeSi showed comparable luminescence intensities and turn-on voltages. Fully characterized $In_xGa_{1-x}As$/GaAs quantum well lasers grown on Ge_xSi_{1-x} substrates will be reported, and implications for future work will be discussed.[1] S.L. Yellen, et al, IEEE Journ. Quant. Elect. QE-29, 2058(1993).

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Lattice Matched $Zn_xBe_{1-x}Te$ Films with GaAs and ZnSe for p-Contact Layers of ZnSe-Based II-VI Laser Diodes: *M. W. Cho*[1]; J. H. Chang[1]; S. Saeki[1]; K. Godo[1]; H. Makino[1]; T. Yao[1]; [1]Tohoku University, Institute for Materials Research, 2-1-1 Katahira, Sendai 980 Japan

A ZnSe-ZnTe pseudograding system has been used for a p-contact layer in ZnSe-based II-VI blue-green laser diodes, which effectively reduced the threshold voltage below 5 V. However, the life time of the laser diode was reported to be around 400 hrs [1]. Previous studies on the degradation mechanisms of GaAs laser diodes suggest that strain caused by the contact layers plays an important role and the reduction of strain induced by the electrode directly lead to the long life time [2]. In view of such experience, it is expected that the strain caused by the large lattice misfit between ZnSe and ZnTe (7.1 %) would play an important role in the degradation mechanisms of the devices. Such a large lattice misfit would induce misfit dislocations threading into the underlying layers during current injection for long time, even if the initial layers are dislocation free [2]. By replacing ZnTe with $Zn_xBe_{1-x}Te$, the problem of lattice mismatching can be perfectly solved. $Zn_xBe_{1-x}Te$ films with compositions of 8.0 % and 5.4 % lattice match with ZnSe and GaAs, respectively. This study will report MBE growth and N-

doping of BeTe films and ZnBeTe films lattice matched with GaAs and ZnSe. The contact resistance of Au/p-ZnSe/p-BeTe structure will be also reported. We have found that the optimum growth conditions for BeTe are achieved under Te-stabilized growth conditions based on X-ray diffraction and atomic force microscopy measurements. The narrowest FWHM value of the (004) X-ray rocking curve of BeTe films was 79 [arcsec]. The Be composition in ZnBeTe films varied in proportion to J(Be)/ (J(Be) + J(Zn)) up to Be<0.2, where J(Be) and J(Zn) are beam equivalent fluxes of Be and Zn. Although the growth conditions of lattice-matched ZnBeTe films with GaAs and ZnSe are not optimized yet, the line width of the (004) X-ray rocking curve is narrower than 100 [arcsec]. We have found that both BeTe films and ZnBeTe films lattice matched with GaAs and ZnSe can be highly p-type doped (p>10^{19}cm^{-3}) with nitrogen, which will enable to make low-resistive p-contact layers. Additional improvement in electrical properties could be expected owing to lower valence band offset for ZnBeTe/ZnSe (or GaAs) than that for ZnTe/ZnSe (or GaAs). Another advantage can be expected when using a p-GaAs substrate. A lattice matched p-ZnBeTe layer can be used as a buffer layer for p-GaAs substrate and is expected to yield good electrical properties because of high p-type dopability and lower valence band offset. It has been demonstrated that selenium and sulfur contamination of the GaAs surface play a crucial role in the formation of defects during the first stage of the II-VI growth [3]. The interface properties between the BeZnTe/GaAs can be much better than either ZnSe/GaAs or ZnSSe/GaAs, because of lower reactivity of Te with the GaAs surface than S or Se. The electrical properties of p-BeTe and p-ZnBeTe layers doped with N were investigated with a thin p-ZnSe layer being deposited onto these layers to protect from oxidation. It is found that a 4 nm thick p-ZnSe capping layer serves as an Ohmic contact layer for underlying p-BeTe or p-ZnBeTe layers as well as a protecting layer from oxidation. Preliminary measurements of the contact resistance of Au for a p-ZnSe/p-BeTe structure by the transmission line method showed a value as low as 8×10^{-5} ohm-cm^2. [1] E. Kato et al., Electron. Lett. 34, 282 (1998). [2] S. Kijima et al., Appl. Phys. Lett. 73, 235 (1998). [3] S. Gua et al., Appl. Phys. Lett. 63, 3107 (1993).

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Selective InAs Contact to GaAs: *Kumar Shiralagi*[1]; Ruth Zhang[1]; Ray Tsui[1]; [1]Motorola Labs, Physical Sciences Research Laboratories, 2100 East Elliot Rd., M/S-EL308, Tempe, AZ 85284 USA

There have been many attempts in the past to obtain good ohmic contacts to GaAs using epitaxially grown InAs and then contacting the InAs using a metal. Any metal deposited on doped InAs forms a good ohmic contact because of its small band gap, high conductivity and charge inversion at the surface. The heterojunction band discontinuity at the InAs/GaAs interface however creates a barrier for electrons and introduces high contact resistance at the interface, and rendering this material combination unsuitable for such applications as FETs and other devices. Several groups were successful in obtaining good contact to GaAs with graded $In_xGa_{1-x}As$ by changing composition from x=0 to x=1 over a thick epitaxial layer. This grading of the layer introduces additional growth complexities. Further, the method is not suitable for selectively grown InAs contact where the selective growth conditions at each composition is going to be different and the continuous changing of growth conditions as a function of composition makes the technique impractical. In this paper, we discuss our success in obtaining good contacts using selective InAs. The top 100 A GaAs layer was heavily doped with multiple delta Si doping. The wafer was then resistlessly patterned and Si doped InAs was selectively grown. Contact resistance better then 0.1 ohm mm was obtained by transmission line measurements. We propose that the multiple delta doping in the GaAs results in multiple narrow tunneling barriers, eliminating the large heterojunction barrier otherwise seen typically. The resistless patterning technique also reduces the chance of residual contamination at the interface. Thus good current through the interface can be obtained. The high density of interfacial dislocations due to lattice mismatch does not hurt the vertical transport. Thus, one-step metallization can be carried out to fabricate FETs in which Al could be used as an ohmic metal for InAs and also as the Schottky gate metal on GaAs. Our results in fabricating functional FETs using this approach will be discussed.

4:30 PM +
Development of Multi-Functional InGaAs-based Ohmic Contacts for GaAs Devices: *Mitsumasa Ogura*[1]; Masanori Murakami[1]; [1]Kyoto University, Dept. of Mats. Sci. and Eng., Div. of Eng. Sci., Kyoto Japan

The conventional GaAs JFET (Junction Field-Effect Transistor) devices use three different electrode materials: AuGeNi for n-type Ohmic contact, TiPtAu for p-type contact, and TiAu for wiring. In our laboratory, our efforts have been made to develop one material which functions both n- and p-type Ohmic contacts and wiring. $In_{0.7}Ga_{0.3}As/Ni/W_2N/W$ contacts which were prepared by a RF(Radio-Frequency) sputtering system were found to provide low contact resistance (R_c) value of 0.2 W-mm for both n- and p-type GaAs after annealing at 550°C.[1],[2] These contacts were extremely thermally stable at 400°C. However, the sheet resistance (R_{sh}) of these contacts were relatively high (12 W/square), and the contacts could not be used as wiring materials. The purpose of the present experiment is to reduce the sheet resistance of InGaAs-based Ohmic contact by depositing Au as the top layer so that this contact will be used as wiring material. The technical issue was to prevent an intermixing of Au and GaAs during annealing at 550°C which is required for Ohmic contact formation. To solve the problem, a thermally stable diffusion barrier layer between the contact materials and Au should be developed. The $In_{0.7}Ga_{0.3}As/Ni/W_2N/Au$ contacts with various thicknesses of the W_2N layers were prepared and the diffusion barrier properties of the W_2N layers were investigated. The $In_{0.7}Ga_{0.3}As$, Ni, and W_2N layers were deposited sequentially on the GaAs substrates in the RF sputtering system, where the W_2N layers were deposited in a mixed gas of 20% N_2/Ar. The Au layers were deposited by a resistance-heater. The R_c values of the present contacts were found to be influenced by the W_2N thickness. The contact with 40 nm-W_2N layer provided the low R_c values of 0.2 W-mm for both n- and p-type GaAs and the R_{sh} value was reduced down to 0.6 W/square after annealing at 550°C for 10s. The electrical properties were did not change after annealing at 400°C for 3h, and the surface morphology of the contacts was extremely smooth. The microstructural analysis showed that Au_xIn or $AuGa_x$ compounds were not formed, suggesting that the Au and GaAs intermixing was prevented by the W_2N layer. The present experiment showed the $In_{0.7}Ga_{0.3}As/Ni/W_2N/Au$ contact functions both n- and p-type Ohmic contacts and wiring. In addition, use of this contact material for GaAs JFET devices will improve the thermal stability and the device performance. [1] C.J. Uchibori, Y. Otani, T. Oku, N. Ono, and M.Murakami, J. Electron. Mater., 26(1997) 410.[2] M. Ogura and M. Murakami, J. Electron. Mater., 27(1998) L64.

4:50 PM
Use of Multi-Quantum Wells for Photoabsorption Enhancement in Compound Semiconductor Solar Cells: *Yoshitaka Okada*[1]; Yoshiyuki Suzuki[1]; Takatoshi Kikuchi[1]; [1]University of Tsukuba, Institute of Mats. Sci., Tennodai 1-1-1, Tsukuba, Ibaraki 305-8573 Japan

The multi-quantum well (MQW) solar cells have gained increasing interest for achieving toward predicted efficiencies in excess of 40% [1]. The fundamental principle is that a MQW inserted within the photoabsorption region of a solar cell diode would define the absorption edge and hence the output current, while the output voltage would be, to the zeroth-order approximation, determined by the wider bandgap (barrier) material. Whether this additional carrier generation and photocurrent expected due to excitonic absorption in MQWs would outweigh the accompanying drop in the terminal voltage due to recombination of carriers trapped in the quantum wells (dark current) is still one of the key issues to be addressed today. In order to reliably investigate their featured characteristics, it is important that one achieves a high material quality, especially in view of minimizing the recombination of photo-generated carriers at the MQW heterointerfaces. For this, we have fabricated InGaAs/GaAs MQWs inserted within the active region of a p-i-n GaAs junction diode by atomic hydrogen-assisted molecular beam epitaxy (H-MBE) technique [2], and by conventional MBE for comparison. The spectral response (SR) of each device was measured at 298K under AM1.5 conditions. In the IR wavelength region of 800nm ~ 1000nm, the SR was increased by ~ 25% in a GaAs single-junction (control) cell, and by ~ 35% in a 10-period MQW cell (In$_{0.07}$Ga$_{0.93}$As quantum well: GaAs barrier = 10nm: 50nm

in thickness) grown by H-MBE compared to MBE. The growth interruption adopted during MQW growth further improved the SR response. The primary reason for the observed improvement in the photovoltaic response in H-MBE samples can be understood, together with works our earlier, that in H-MBE, the electrical activity of deep-level defects and hence diode leakage current are drastically reduced due to H passivation [3]. Further, the MQW heterointerfaces are more atomically smooth in H-MBE samples than in MBE. Thus the carrier recombination at the heterointerfaces are expected to be efficiently suppressed thereby improving the collection of carriers escaping from the quantum wells. High efficiency cells could be realized by using H-MBE grown MQWs with further optimized cell design, In composition and increased photoabsorption volume. [1] K. W. J. Barnham and G. Duggan, J. Appl. Phys. 67, 3490 (1990). [2] Y. Okada, H. Shimomura and M. Kawabe, J. Appl. Phys. 73, 7376 (1993).[3] Y. Okada, J. S. Harris, Jr. and W. Goetz, J. Appl. Phys. 80, 4770 (1996).

Session H. Electronic Transport in Organic & Molecular Materials

Wednesday PM Room: Santa Barbara Harbor
June 30, 1999 Location: University Center

Session Chairs: Shelby Nelson, Colby College, Waterville, ME USA; David Janes, Purdue University, West Lafayette, IN USA

1:30 PM *Invited
What Determines the Resistance of a Molecule?: *Supriyo Datta*[1]; [1]Purdue University, 1285 Electr. Eng. Bldg.West Lafayette, IN 47907

In this talk we will start by discussing what it means to talk about the "resistance" of something as small as a molecule. Next we will present some recent experimental work that measures the resistance of individual organic molecules by inserting special functional groups at the ends which attach to the surface of a metal like microscopic "alligator clips". We will then show how the experimental results can be understood in terms of a simple model, identifying the important factors that affect the shape of the current-voltage characteristics. Finally we will address the question of how molecules can be designed to exhibit specific properties such as rectification or negative differential resistance.

2:10 PM
Simulation of Molecular Devices from First-Principle: *Massimiliano Di Ventra*[1]; Norton Lang[2]; Sokrates T. Pantelides[1]; [1]Vanderbilt University, Phys. and Astronomy, Stevenson Center, Nashville, TN 37235 USA; [2]IBM, Research Div., Thomas J. Watson Research Center, Yorktown Heights, New York, NY 10598 USA

Devices based on nanostructures (molecules, nanotubes, nanoclusters) have recently received much attention for their possible replacement of conventional electronic components. At these length scales, conventional device simulations based on Boltzmann's equation must be replaced by fully quantum-mechanical approaches. We present the first parameter-free quantum mechanical simulations of a molecular device that has already been studied experimentally by Reed et al. [1], namely a benzene-1,4-dithiolate molecule between gold electrodes. The theoretical I-V curve has the same overall shape as the experimental curve — reflecting the electronic structure of the molecule as modified by the electric field — but the absolute value of the current is very sensitive to contact chemistry and geometry. In particular the presence of a single gold atom between the molecule and the electrode surface reduces the conductance by about two orders of magnitude. Replacement of the single gold atom by an aluminum atom, whose p orbitals couple more effectively with the molecule's p orbitals, increases the conductance by about an order of magnitude. Such calculations will, therefore, play a

crucial role in future device design and contact Eng.. [1] M. Reed et al., Sci. 278, 252 (1997) Work supported in part by NSF grant 98-03768.

2:30 PM +

Electronic Transport Characteristics Through Diisocyanide: *Jia Chen*[1]; Laurie E. Calvet[1]; Chongwu Zhou[1]; Mark A. Reed[1]; Dustin W. Carr[2]; Desiree S. Grubisha[3]; Dennis W. Bennett[3]; [1]Yale University, Elect. Eng. Dept., Rm. 509, 15 Prospect St., New Haven, CT 06520 USA; [2]Cornell University, Cornell Nanofabrication Facility, G05 Knight Lab, Ithaca, NY 14853 USA; [3]University of Wisconsin-Milwaukee, Dept. of Chem. and Biochem., 3210 North Cramer St., Milwaukee, WI 53211 USA

The investigation of electronic transport in molecular-scale systems is of interest from both a fundamental and potential application standpoint. We report the first measurements of electrical transport properties in a new type of self-assembled molecule-metal junction, specifically 1,4-phenylene diisocyanide with gold contacts. Experiments were conducted on symmetric nanoscale metal(gold)/molecule/metal(gold) junctions. Variable temperature conductance measurements revealed that thermionic emission dominates at high electric field, while hopping conduction takes over at low electric field. A thermal barrier of 0.4 eV was obtained for field larger than 1 MV/cm; below 1 MV/cm, a hopping barrier of 0.3 eV was found. This is the first direct electrical measurement of the contact potential between a metal and a diisocyanide SAM. Comparison with other molecule-metal junction systems (such as gold-thiol) will be discussed.

2:50 PM

Improved Contacts for Organic Electronic Devices Using Self-Assembled Charge Transfer Materials: *Jianna Wang*[1]; David J. J. Gundlach[1]; Chung-Chen Kuo[1]; Thomas N. Jackson[1]; [1]The Pennsylvania State University, Center for Thin Film Devices, and Electr. Mats. and Processing Research Laboratory, 121 EE East, University Park, PA 16802 USA

Contacts to organic active layers in thin film transistors (TFTs) and light emitting devices are often problematic. In particular, TFTs often make use of the high resistivity of the active layer to achieve low off currents at usefully low operating voltages, but the same high resistivity can make current injection at contacts difficult. Generally, metals or other conductors with selected work functions are used to improve contacts, but with limited success. Charge exchange materials have also been investigated [1]; such materials can have improved contact characteristics, but the charge exchange molecule can move during device processing or operation. We have fabricated pentacene TFTs with modified drain-source contacts using charge transfer (CT) compounds bound to device contacts using a self-assembly approach. The self-assembly layer is selectively formed on the drain-source regions, and therefore no additional patterning is required. Since the CT molecule is chemically bonded on the drain-source metal, an immobilized CT complex is formed with the organic semiconductor. The formation of the CT complex is expected to decrease contact resistance and increase the extrinsic field-effect mobility of the OTFT. In this work, we selected a CT compound with a thiol group which forms a chemical bond to gold. For pentacene, a p-acceptor, 2-mercapto 5-nitrobenzimidazole (MNB), was used. Substrates with prepatterned gold drain-source contacts were immersed into an alcohol solution of MNB. FTIR spectra showed that the self-assembled monolayer is formed only on the gold electrodes, not elsewhere. After the contact treatment, the surface is ready for the active layer deposition and device or circuit completion. TFTs with contacts treated with an electron acceptor compound had improved carrier mobility and higher current on/off ratio, compared to devices with untreated contacts. On the other hand, TFTs treated with an electron donor compound had degraded characteristics compared to untreated devices. 1. Francis Garnier, Faycal Kouki, Rhiad Hajlaoi, and Gilles Horowitz, Material Research Society Bulletin, June 1997, 52-56

3:10 PM   Break

3:30 PM   *Invited

High Mobility Charge Transport in Aromatic Hydrocarbon Single Crystals: *Jan Hendrik Schön*[1]; Steffen Berg[1]; Christian Kloc[1]; Bertram Batlogg[1]; [1]Bell Laboratories, Lucent Technologies, 700 Mountain Ave., Murray Hill, NJ 07974-0636 USA

Organic field-effect transitors based on aromatic hydrocarbons like pentacene have reached performance similar to a-Si:H with mobilities above 1 cm2Vs and on/off-ratios up to 10[8]. Despite this impressive technological progress, the knowledge of the charge transport mechanism in these organic semiconductors is still incomplete. In order to determine the intrinsic transport properties, high quality single crystals of aromatic hydrocarbons, like pentacene and rubrene, have been grown from the vapor phase. The electrical properties of these materials were investigated by means of space charge limited current spectroscopy. Conductivity, acceptor concentrations, trap densities, their activation energies, and the hole mobility were determined as function of temperature, applied electric field, and crystal orientation. The hole mobility increases from approximately 2 cm2/Vs at room-temperature to more than 200 cm2/Vs at 20K in pentacene following a power law. The observed sublinear electric field dependence of the hole velocity can be explained by scattering at acoustic phonons. The bandwidth and effective mass can be estimated from the high field saturation velocity of the charge carriers. In pentacene, a value of 0.4 eV for the low temperature bandwidth has been determined, which decreases with increasing temperature due to coupling with optical phonons. The combination of the high mobility, the power-law temperature dependence, the large extracted bandwidth, and the fact that the calculated mean free path exceeds many lattice constants suggest that the charge transport in these organic semiconductor can be described by conventional band-theory.

4:10 PM

High Mobility Polymer Thin Film Transistors Based on Copolymers of Thiophene and 3-Hexyl Thiophene: *Jianna Wang*[1]; David J. Gundlach[1]; Alan J. Benesi[2]; Thomas N. Jackson[1]; [1]The Pennsylvania State University, Center for Thin Film Devices, and Electr. Mats. and Processing Research Laboratory, 121 EE East, University Park, PA 16802 USA; [2]The Pennsylvania State University, Chem. Dept., University Park, PA 16802 USA

We have fabricated polymer thin film transistors (PTFTs) using solution-cast copolymers of thiophene and 3-hexyl thiophene with field effect mobility is as high as 0.046 cm2/V-s, the highest reported for PTFTs using non-regioregular polythiophene. Solution processible PTFTs are of interest for the fabrication of low-cost, flexible displays, and other large-area electronic uses. Poly(3-alkyl thiophenes) are popular solution-castable electronic polymers because of their excellent environmental stability. However, the carrier mobility of solution cast poly(3-alkyl thiophene) is relatively low, typically in the range of 10-8 to 10-3 cm2/V-s. Higher mobility, 0.05-0.1 cm2/V-s, has been reported for regioregular poly(3-hexyl thiophene) [1], however, the complicated regiosynthesis significantly increases the material cost. In previous work [2], we copolymerized 3-methyl thiophene and 3-hexyl thiophene using FeCl3 as the oxidant. This one-step easy synthesis offers much higher yield than the multi-step regiosynthesis. The insertion of a smaller molecule, 3-methyl thiophene, into the 3-hexyl thiophene chain enhances the formation of longer conjugated length, and therefore tends to increase carrier mobility, while the larger molecule, 3-hexyl thiophene, provides sufficient steric hindrance to allow solubility in common organic solvents. PTFTs based on copolymer of 3-methyl thiophene and 3-hexyl thiophene have field effect mobility as high as 0.026 cm2/V-s [2]. We have now investigated copolymers based on thiophene and 3-hexyl thiophene. Even with the small thiophene molecule, good copolymer solubility is maintained for thiophene monomer feed fraction as large as 5%. Devices fabricated from copolymer synthesized with a thiophene monomer feed fraction of 5% have good characteristics with field effect mobility as large as 0.046 cm2/V-s. [1] H. Sirringhaus, N. Tessler, P. Brown, and R. H. Friend, Sci., vol. 280, 1998, 1741 [2] Jianna Wang, Yen-Yi-Lin, Weidong Qian, and Thomas N. Jackson, MRS Abstract, Fall 1998, R4.4, 327

4:30 PM +

Contact Limited Performance of Pentacene Thin Film Transistors: *David J. Gundlach*[1]; Jonathan A. Nichols[1]; Chung-Chen Kuo[1]; Hagen Klauk[1]; Chris D. Sheraw[1]; Darrell G. Schlom[2]; Thomas N. Jackson[1]; [1]The Pennsylvania State University, Dept. of Elect. Eng., 121

Elect. Eng. East, University Park, PA 16802 USA; [2]The Pennsylvania State University, Dept. of Mats. Sci. and Eng., 103 Steidle Bldg., University Park, PA 16802-5005 USA

Because organic electronic materials are often sensitive to the chemicals used in photolithographic processing; devices fabricated by depositing the active organic material onto patterned source/drain contacts (photolithographically defined prior to the organic active layer deposition) are of interest. However, TFTs fabricated using pre-patterned bottom contacts often have reduced performance compared to devices fabricated using top contacts (typically deposited through a shadow mask)[1]. To improve our understanding of bottom contacts we have fabricated TFTs with pre-patterned source/drain contacts of platinum (Pt), palladium (Pd), gold (Au), nickel (Ni), and aluminum (Al) using heavily-doped, thermally-oxidized silicon as the substrate, gate dielectric, and gate electrode. All metals were deposited by ion beam sputtering to give high-quality, thin, smooth films, and contacts were defined photolithographically using a two-layer resist lift-off process. Pentacene, the active layer, was deposited by thermal evaporation. The surface morphology was monitored by atomic force microscopy (AFM) and the structural order was characterized by x-ray diffraction. TFTs fabricated using Pd, Au, or Pt source/drain contacts had the best performance with little difference observed between these relatively stable metals. Devices fabricated using Ni or Al contacts showed strong space charge limited current (SCLC) effects at small source-drain biases and reduced extrinsic mobility, possibly due to the presence of a native oxide for these less stable metals (in previous work we have observed only small work function related contact effects for shadow-masked top contacts). TFTs using Ni or Al as the source contact and Pd as the drain contact had characteristics similar to devices using Ni or Al for both the source and drain contacts. When the source/drain contacts were reversed (Pd as the source contact and Ni or Al as the drain contact), TFT performance was similar to TFTs fabricated using Pd for both the source and drain contacts. This indicates that carrier injection at the source contact can limit device performance and that carrier extraction at the drain contact is less problematic. Correlations between the electrical properties and structural properties revealed by AFM and x-ray diffraction will be discussed. 1. Y-Y. Lin, D. J. Gundlach, and T. N. Jackson, 54th Device Research Conference Digest, p. 80-81, June 1996.

4:50 PM Late News

Session I. Column IV Heterostructures and Devices

Wednesday PM   Room: Flying A Studios
June 30, 1999   Location: University Center

Session Chairs: Eugene Fitzgerald, MIT, Cambridge, MA USA; Ya-Hong Xie, UCLA, Dept. of Mats. Sci. & Eng., Los Angeles, CA USA

1:30 PM +
Exploitation of Facet Formations in SiGe/Si Selective Epitaxial Growth for Achieving a Nanometer Template: *Greg D. U'Ren*[1]; Mark S. Goorsky[1]; Kang L. Wang[2]; [1]UCLA, Dept. of Mats. Sci. and Eng., 6532 Boelter Hall, 405 Hilgard Ave., Los Angeles, CA 90095-1595 USA; [2]UCLA, Dept. of Elect. Eng., 405 Hilgard Ave., Los Angeles, CA 90095-1594 USA

Gas-source molecular beam epitaxy was used to investigate facet formations occurring in the selective epitaxial growth of $Si_{1-x}Ge_x/Si$ psuedomorphic heterostructures ($x \pounds 0.2$). We carried out experiments on nominally on-axis (100) Si substrates masked with 50 - 60 nm thermally grown SiO_2. Arrays of wires varying in pitch (0.5 - 25 mm) were defined by optical lithography techniques. A sidewall orientation

parallel to the <011> directions was used to exploit growth of {hkk}-type facets. Cross-section transmission electron microscopy was employed to monitor the development of both {311}-type and {111}-type facets as function of epi thickness and window size. Phemonologically similar to Si, facet growth in SiGe SEG initiates with the {311}-type, but it differs in that as growth proceeds it continues to dominate over the {111}-type facet by a ratio of 3:1. The {111} facet does nucleate and grow, but as the epi thickness increases it does not completely consume the {3 11} facet as would be expected if surface energy were the sole driving force. The combination of the {111} and {311} facet growth leads to an overall lateral reduction of the (100) mesa top at an estimated rate of 2-3:1[laterals reduction (x,y):epi thickness (z)]. The reduction rate accelerates due to the dominant {311} facet, which has a 1.6 larger projection onto the (100) surface than the {111} facet, more quickly promoting the lateral reduction. In this way, the lateral dimension can be reduced beyond the original lithographic definition, advantageous for fabrication of a nanoscale template, which can be then used for growth of SiGe heterostructures or a Ge island array. Triple axis x-ray diffraction measurements of the selective epi determined that the crystalline perfection is high and is not compromised by the presence of facet growth. For the 0.5 mm lateral features that had undergone the reduction process to fabricate a 15 nm template, a tri-axial stress-state was observed. Parallel to the array of periodic structures, the additional in-plane elastic relaxation as a result of the additional free surfaces was quantified. Experimentally, reciprocal space mapping of both symmetric and asymmetric diffraction geometries was carried out, and the results were compared to simulated contour maps generated using a kinematical approach that determined $e_{xx} = (2 \pm 3) \times 10^{-5}$. The driving force for the mechanical response is the inherent misfit strain, in this example $e_{zz} = 5.23 \times 10^{-3}$. Perpendicular to the array however, the selective epi is completely commensurate, i.e. $e_{yy} \sim 0$. The in-plane asymmetry indicates an overall, but small, orthorhombic lattice distortion in the nanometer template.

1:50 PM +
Selective Si Epitaxial Growth Using Ultrathin Oxide Mask Formed By Resistless Patterning: *Shawn G. Thomas*[1]; Greg D. U'Ren[2]; Mark S. Goorsky[2]; Kang L. Wang[1]; [1]University of California, Los Angeles, Elect. Eng. Dept., 63-109 Eng. IV, Los Angeles, CA 90095-1595; [2]University of California, Los Angeles, Mats. Sci. and Eng. Dept., Los Angeles, CA 90095-1595

Previously, selective epitaxial growth (SEG) of InAs on GaAs has been demonstrated using a 1.5 nm thick oxide mask using the resistless patterning technique described by Shiralagi et al. [Applied Phys. Lett. 71 (20), 1997]. In this paper, we report the results of our efforts at selective Si homo-epitaxial growth using a 1.0 - 2.0 nm thick oxide mask using a similar patterning technique on Si and via gas source molecular beam epitaxy (GSMBE). Resistless patterning was carried out by placing a chrome mask over a hydrogen passivated Si wafer and exposing it to UV light (185 nm) in an ozone cleaner in a room air ambient. Selective growth was performed by GSMBE using disilane as the precursor. Prior to growth, the substrate was heated to a temperature of 615°C for hydrogen desorption. In an effort to maintain the integrity of the masking oxide, the in-situ thermal cleaning process was forgone, initiating Si deposition once the substrate reached a temperature of 615°C and with a (1x1) reconstruction. As growth proceeded, the (1x1) pattern began to assume a surface faceting character. For all experiments, the absence of Debye-Scherrer rings superimposed onto the (1x1) suggests that the SEG was completely selective for the thickest epi. No simultaneous growth of polycrystalline deposits on the masking layer suggests that the SiO_2 was of high quality and free of heterogeneities. The post-growth surface morphology was observed using Normanski interference microscopy and the masked and unmasked regions were clearly delineated. The step height was measured to be 140 - 150 nm, once again indicating a loss in selectivity beyond this thickness. Additionally, x-ray diffraction analysis was performed to gauge the crystalline quality of the SEG film. Based on our experiments, we have demonstrated that it is possible to use an ultra-thin oxide mask to achieve selective Si growth via GSMBE to thickness of 150 nm. Results of this study are compared to observations made in a CVD reactor using dichlorosilane where the presence of chlorine pre-

vents thicker Si growth. Possible applications of this simplified patterning technique and selective growth will be discussed.

2:10 PM
Electrical and Structure Characterization of Single Crystalline SiGe Formed by Ge Deposition and RTP: *Y. H. Wu*[1]; W. J. Chen[2]; Albert Chin[1]; C. Tsai[1]; [1]National Chiao Tung University, Dept. of Electr. Eng., Hsinchu, Taiwan ROC; [2]National Huwei Institute of Technology, Dept. of Mechanical Mats. Eng., Huwei, Taiwan ROC

SiGe alloys have been found to be a very promising material because of its potentially useful electronic and optical properties. In general, the SiGe/Si heterojunction can be grown by UHVCVD, MBE, or even by solid phase epitaxy from Ge ion implantation. However, UHVCVD or MBE require expansive equipment and Ge implantation-formed SiGe does not have a uniform Ge composition. In this work, we have presented a simple method to form single crystalline SiGe by depositing amorphous Ge on Si substrate followed by a rapid thermal annealing. Selective formation of SiGe can be also easily achieved by liftoff. Similar to MBE or UHVCVD epitaxy, the suppression of native oxide is of paramount importance to form epitaxial SiGe rather than the polycrystalline one. To overcome this problem, we have used HF-vapor treatment to passivate the Si surface and suppress the native oxide formation. From x-ray diffraction and TEM analysis, single crystalline SiGe is formed by this method with HF-vapor passivation. A uniform $Si_{0.3}Ge_{0.7}$ layer of ~50nm is confirmed by SIMS measurement. The crystalline quality is strongly degraded by native oxide that even becomes poly-crystalline structure. Similar quality improvement has been observed by us on ultra-thin oxide with an atomically smooth interface. To further investigate the practicability of this SiGe, we have fabricated PMOS transistor and MOS-capacitor to study its electrical characteristics. As comparing to standard Si-based PMOS, the SiGe PMOSFET showed increased output current Dr. by a factor of two. This current Dr. improvement is due to increased hole mobility. Peak mobility value of 251 cm2/Vs is measured in the SiGe PMOSFET that is about two times higher than Si. In addition to the high mobility, a low source/drain junction-leakage of 2.7x10-8 A/cm2 is measured at -3.3V that is compatible to the standard Si junction. This low junction leakage can be also explained by the similar process to form silicide. Another important advantage of this process is the capability to form high quality SiGe oxide. A very high breakdown electrical field is 15MV/cm is measured that is close to SiO2. The breakdown field is carefully measured and oxide thickness is directly determined by F-N tunneling. The good oxide quality is also demonstrated by the high reliability of charge-to-breakdown of 6 C/cm2. Although exact mechanism of achieving this high quality oxide is still under investigation, it may be related to the high RTP temperature and the strain relaxation in SiGe. In conclusion, high quality SiGe can be formed by a simple, inexpensive and VLSI compatible process.

2:30 PM
Surfactant Mediated Epitaxy of Ge/Si Heterostructures for Device Applications: *Karl R. Hofmann*[1]; Martin Kammler[1]; Dirk Reinking[1]; Michael Horn-von Hoegen[2]; [1]University of Hannover, Inst. f. Halbleitertechnologie, Appelstrasse 11 A, D-30167 Hannover Germany; [2]University of Hannover, Inst. F. Festkoerperphysik, Appelstrasse 2, D-30167 Hannover Germany

The deliberate use of an adsorbed monolayer of a group V element as surfactant, here Sb, during Ge/Si epitaxy inhibits island formation and allows the growth of smooth and continuous epitaxial Ge films on Si. On Si(111) the 4.2 % lattice mismatch between Si and Ge is accommodated by a quasiperiodic array of misfit dislocations which is completely confined to the Si-Ge interface. With this surfactant mediated epitaxy (SME), relaxed Ge-layers of arbitrary thickness larger than 10 nm can directly be grown on Si substrates. Thus high-quality Ge device structures, which are CMOS-compatible, can be placed on Si substrates without the use of thick relaxed graded SiGe buffer layers. We have investigated the structural and electrical properties of such Ge-layers grown into oxide windows on wafers pre-structured with a conventional LOCOS process and on bare Si substrates. The layers were analyzed by AFM, TEM, XRD, high-resolution LEED, SEM, and lateral Hall mobility and vertical Ge/Si diode transport measurements. The excellent crystal quality of these Ge films is revealed by X-ray diffraction which

shows extremely sharp diffraction peaks with the Ge bulk lattice constant. Furthermore, very high electron Hall mobilities of 3200 cm2/Vs at room-temperature are routinely obtained (12000 cm 2/Vs at 77K) for 1000 nm thick Ge films on Si(111). These mobility values correspond to high-quality bulk Ge mobility values with low Sb background n-type doping as reflected by Hall electron densities of about $1*10^{16} cm^{-3}$. This low background doping concentration of the surfactant Sb is three orders of magnitude below the Sb solid solubility in Ge. We have recently fabricated the first devices - Ge p-channel MOSFETs - on a Si substrate using SME. We will report results on the SME growth of strained SiGe MODFET structures on thin relaxed SiGe alloy layers on Si substrates demonstrating the potential of this growth technique for a variety of interesting device applications.

2:50 PM +
Direct Growth of Ge on Si for Integrated Si Microphotonic Photodetectors: *Hsin-Chiao Luan*[1]; A. M. Agarwal[1]; Kzumi Wada[1]; E. A. Fitzgerald[1]; L. C. Kimerling[1]; [1]Massachusetts Institute of Technology, Dept. of Mats. Sci. and Eng., 13-4130, 77 Mass Ave, Cambridge, MA 02139 USA

The successful development of integrated Si microphotonic circuits requires the integration of efficient photodetectors operating at 1.3um or 1.54um with Si CMOS devices and polySi waveguides. Ge with its high absorption coefficient at these two wavelengths is a candidate material for such an application. However, the 4% lattice mismatch between Ge and Si results in island formation when Ge is grown directly on Si. SiGe graded buffer technology can provide high quality Ge films on Si with threading dislocation densities as low as 2x10^6cm^-2. This technology, however, requires a 10um thick graded buffer for grading from Si to pure Ge. Si CMOS devices are relatively planar and occupy only the region close to the top surface of Si wafers. For simple process integration of Ge photodetectors with Si CMOS devices it is desirable to grow a thin high quality Ge film directly on Si. In this work we report the development of a process for the growth of Ge films with low threading dislocation densities on Si. We have investigated the quality of Ge, grown on Si, by a two-step UHV-CVD process followed by cyclic thermal annealing. Thin Ge films were first grown on Si at 300ºC. Growth at low temperatures reduced the diffusion of Ge atoms and prevented island formation. After 60nm of Ge was grown, the furnace temperature was raised to 600ºC and 1um of Ge was deposited. The threading dislocation density in the as-grown Ge (measured with plan-view TEM) was 9.5±0.2x10^8cm^-2. Cyclic thermal annealing reduced the threading dislocation density to 2.2± 0.3x10^7cm^-2. The effect of thermal annealing temperature, annealing time, and the number of thermal cycles on threading dislocation density was studied. We propose a simple model for dislocation motion and reactions due to differential thermal stress to account for the reduction of threading dislocations. To determine the applicability of Ge films grown on Si using two-step technique, we have studied the effect of threading dislocations on the GHz operation of Ge photodetectors. Using a model that correlates the junction leakage current and threading dislocation density we reported earlier, we compared the leakage current noise and photoelectron noise. The optical power required to obtain a bit-error-rate of 10^-9 was calculated as a function of detector speed and total leakage current. We find that the noise due to carrier-generation at threading dislocations (10^7cm^-2) is not fatal to GHz operation of Ge photodetectors. Based on our model, direct growth of Ge on Si is a viable process for the integration of high speed Ge photodetectors in Si CMOS technology.

3:10 PM Break

3:30 PM +
Boron Segregation in Polycrystalline Si(1-x-y)Ge(x)C(y) Alloys: *Eric Jonathan Stewart*[1]; Malcolm S. Carroll[1]; Chia-Lin Chang[1]; James C. Sturm[1]; [1]Princeton University, Dept. of Elect. Eng., Center for Photonics and Optoelectronic Mats., J303 Eng. Quad, Olden St., Princeton, NJ 08544 USA

Polycrystalline $Si_{1-x-y}Ge_xC_y$ gates have been previously shown to greatly reduce the penetration of boron through thin gate oxides in PMOS structures[1]. PMOS capacitors made with a layer of poly $Si_{1-x-y}Ge_xC_y$ in the heavily boron doped (~10^21/cm3) gate electrode had greater

resistance to boron penetration through the gate oxide than those with all polycrystalline Si or polycrystalline $Si_{1-x}Ge_x$ gate electrodes. Boron readily diffused out of the poly Si and poly $Si_{1-x}Ge_x$ gates and through the gate oxide during high temperature anneals (900°C). In the structures with poly $Si_{1-x-y}Ge_xC_y$ gates, however, boron accumulated in the $Si_{1-x-y}Ge_xC_y$ layer, significantly reducing diffusion through the gate oxide. This effect appears to be due to boron preferentially remaining in poly $Si_{1-x-y}Ge_xC_y$ layers, possibly because it has a lower chemical potential in $Si_{1-x-y}Ge_xC_y$ than in Si or $Si_{1-x}Ge_x$, not due to the lower diffusion coefficient of boron in crystalline SiGeC as has recently been reported[2]. In this abstract we report, to the best of our knowledge, the first independent evidence of boron segregation into both polycrystalline and crystalline $Si_{1-x-y}Ge_xC_y$ from Si. Layers of poly $Si_{1-x}Ge_x$ and poly $Si_{1-x-y}Ge_xC_y$ were grown on a wet chemically oxidized p-type substrate by Rapid Thermal Chemical Vapor Deposition(RTCVD). Each SiGe(C) layer was isolated by polycrystalline silicon spacer layers on both sides. The poly $Si_{1-x}Ge_x$ and $Si_{1-x-y}Ge_xC_y$ layers were grown at 625°C and x~0.2; the poly Si spacer layers were grown at 700°C. All layers were doped in-situ with boron at $~1x10^{20}/cm^3$. Silane, germane, diborane, and methylsilane were used as source gases in a hydrogen carrier gas at 6 torr. Oxygen levels in all layers were much less than boron or carbon levels. These structures were then annealed at 800°C for 18 hours in nitrogen. Concentration vs. depth profiles of all relevant materials in the structure were obtained by Secondary Ion Mass Spectroscopy (SIMS). Boron clearly segregated from the silicon into the $Si_{1-x-y}Ge_xC_y$ layers during the anneal. In the poly $Si_{1-x}Ge_x$ layers, boron outdiffused into the adjacent poly Si layers, causing concentration profiles to flatten out. In the poly $Si_{1-x-y}Ge_xC_y$ layers with significant carbon content(>0.1%), boron concentrations actually increased after annealing, with boron levels decreasing in the adjacent poly Si layers. In the $Si_{1-x-y}Ge_xC_y$ layer with ~1% carbon, the boron levels after annealing were approximately four times higher than in the adjacent silicon layers. Any tendency of boron to segregate to polycrystalline $Si_{1-x}Ge_x$ layers without carbon was an order of magnitude weaker, consistent with observations in crystalline $Si_{1-x}Ge_x/Si$ samples[3]. We have also observed large segregation of boron to $Si_{1-x-y}Ge_xC_y$ in crystalline $Si_{1-x-y}Ge_xC_y/Si$ samples. Initial electrical data suggests that the boron is still electrically active after segregation to $Si_{1-x-y}Ge_xC_y$, and does not segregate to electrically inactive defect sites. This is fortuitous for device applications such as polycrystalline gates. Existing models for boron segregation in the $Si_{1-x}Ge_x/Si$ system are based on lattice strain and valence band offset arguments[4]. From both of these arguments, less boron diffusion to $Si_{1-x-y}Ge_xC_y$ than $Si_{1-x}Ge_x$ would be expected. A new model to explain our data will be presented. References 1. C. L. Chang and J.C. Sturm, "Polycrystalline $Si_{1-x-y}Ge_xC_y$ for suppression of boron penetration in PMOS structures," Materials Research Society Symposium Proceeding, 525, (1998). 2. M. S. Carroll, L. D. Lanzerotti, and J.C. Sturm, "Quantitative Measurement of Reduction of Boron Diffusion by Substitutional Carbon Incorporation," Materials Research Society Symposium Proceeding, 527, (1998). 3. S. M. Hu, D. C. Ahlgren, P. A. Ronsheim, and J. O. Chu, "Experimental Study of Diffusion and Segregation in a Si-(GexSi1-x) Heterostructure," Physical Review Letters, 67:(11) 1450-1453, (1991). 4. S. M. Hu, "Diffusion and Segregation in Inhomogenous Media and the GexSi1-x Heterostructure," Physical Review Letters, 63:(22) 2492-2495, (1989).

3:50 PM

X-Ray Diffraction and Transmission Electron Microscopy Study of the Development of Texture in Polycrystalline $Si_{1-x}Ge_x$ Thin Films: *Wei Qin*[1]; D. G. Ast[2]; T. I. Kamins[3]; [1]Institute of Microelectronics, 11 Sci. Park Rd., Singapore Sci. Park II, Singapore 117685 ROS; [2]Cornell University, Mats. Sci. & Eng. Dept., Ithaca, NY 14853 USA; [3]Hewlett-Packard Laboratories, Palo Alto, CA 94303-0867 USA

Intrinsic, 300 nm thick $Si_{1-x}Ge_x$ films with x=0.02, 0.13, and 0.31 respectively, and a control polysilicon film, x=0 were deposited by CVD at a pressure of 100 Torr, on a 60 nm polysilicon seed layer at temperatures between 600 and 800°C, depending on Ge fraction. SiH_2Cl_2 was used for polysilicon deposition and SiH_2Cl_2 mixed with GeH_4 for SiGe. Polysilicon seed layer was grown by CVD on SiO_2 using SiH_4 at 650°C. X-ray diffraction and transmission electron diffraction (TED) study on planar samples showed that polysilicon control film and SiGe films had {110} texture. X-ray diffraction of a 'seed layer only' sample indicated that grains in seed layer were randomly oriented. The development of texture was studied by taking TED patterns of cross-section samples, employing conditions such that electron beam illuminated top layer only, or using a larger beam size, both seed layer and top layer. Comparison of relative diffraction intensity of arcs contributed by the {110} texture to total diffracted intensity was used to obtain information on the texture in seed layer. Consistent with x-ray diffraction result, {110} texture appears weak or absent in the seed layer, indicating that texture in the seed layer remained unchanged. To determine the width of distribution of otientation around fiber axis, a, we measured the spread of {110} arc on TED patterns for samples containing diffrerent Ge fractions. This analysis showed very similar value for a in all Ge containing films, about 25°. The a in polysilicon control film is about 31°. Analysis of the x-ray diffraction intensity showed that about 46 to 54% of grains in films were {110} oriented, the fraction oriented increased with increasing Ge fraction, indicating that the addition of Ge facilitates the development of {110} texture. Other orientations present, listed in decreasing sequence according to their texture intensity, were {311}, {111}, {100}, and {331}. TED of wedge-shaped planar specimens showed that {110} was dominant texture during entire growth process in all films, and that the degree of this texture increased during growth. The grain size in the top layer was found to range from 45 nm to 81 nm by TEM, depending on Ge fraction. Microtwins with common {110}orientation were found in all films. Cross-section TEM images showed that all films possessed a columnar structure, and that numerous V-shape grains formed near that op of the film. The above results indicate that the orientation of the polycrystalline seed layer does not play a critical role in determining the texture that develops in subsequently deposited SiGe films, when the seed layer has no preferred texture, and that the {110} texture, once initiated, rapidly increases during subsequent film growth.

4:10 PM

Diamond Epitaxy for Electronic Devices: *Aleksandar Aleksov*[1]; Mike Kunze[1]; Andrei Vescan[1]; Wolfgang Ebert[1]; Erhard Kohn[1]; Andreas Bergmaier[2]; Guenther Dollinger[2]; [1]University of Ulm, Dept. of Electron Devices and Circuits, Albert-Einstein-Allee 45, Ulm D-89081 Germany; [2]Technische Universitaet Muenchen, Dept. E12, Beschleunigerlabor der LMU/TUM, Muenchen Germany

Diamond is commonly considered a quite unusual and difficult semiconductor material. Nevertheless many electronic devices have been realized so that the extraordinary potential of this ultra wide bandgap semiconductor can be well assessed. In this presentation we would like to discuss the epitaxial procedures for the most advanced structures, namely d-doped channel, lossy dielectric FETs and pnp BJTs. The epitaxial growth of high crystal quality diamond was performed by MWPCVD using an approximate 1.5%-CH4 in H2 mixture at 30Torr and 600°C-800°C. The growth rates range from 5nm/min to 14nm/min. The only technically relevant dopants in diamond are boron and nitrogen (phosphorus is being considered as a shallow donor, but has not yet been implemented in complex device structures). A method of doping diamond during epitaxial growth by using a boron rod as a solid doping source was developed. With this doping method it is possible to fabricate steep doping profiles (delta spikes), homogeneous and degenerately doped (NA>1020cm-3) diamond films, needed for the fabrication of diamond FETs and BJTs. The activation energy of boron is EA=0.38eV. At NA»1020cm-3 the EA disappears due to miniband formation and overlap with the valence band. The maximum controllable sheet charge density in FET channels pSmax is presently limited to 2×1013cm-2. This leads to d-doped channels with channel widths <3nm for full activation. Epitaxially grown d-doped films were analyzed by elastic recoil detection giving a FWHM of 4nm with peak NA>2.5×1020cm-3. Nitrogen is a very deep donor with ED=1.7eV. Nevertheless it is possible to fabricate abrupt boron/nitrogen pn-junctions that operate even at R.T. This pn-junctions were then applied in BJTs and as control diodes in FETs. Abrupt junctions were fabricated by using growth interrupts, which are not detrimental in the case of diamond. Deep donor and acceptor levels are common in many wide band gap semiconductor materials, with the extreme case of diamond. Problems concerning diamond are similar but an order of magnitude higher than in other wide gap materials like SiC and III-Nitrides. Nevertheless device operation, both FET and BJT has been demonstrated. Diamond d-channel FETs with a lossy dielectric boron/nitrogen control junction

and channels with EA=55meV were fabricated. This allowed for the first time FET operation in liquid nitrogen. Current densities of 20mA/mm at 200°C for a device with LG=20mm were obtained. Bipolar action was observed in BJT p+/n/p- structures even at R.T. both in common base and in common emitter configuration displaying an a>0.9 in common base configuration.

4:30 PM +

Epitaxial Growth of Si/Y2O3/Si: A Potential SOS Structure:
Michael Edward Hunter[1]; Mason J. Reed[1]; John C. Roberts[2]; N. A. El-Masry[1]; S. M. Bedair[2]; [1]NC State University, Mats. Sci. and Eng., 232 Riddick Labs, Box 7916, Raleigh, NC 27695 USA; [2]NC State University, Elect. and Comp. Eng., 232 Daniels Hall, P.O. Box 7911, Raleigh, NC 27695 USA

Silicon on insulator structures have been the focus of much attention due to their potential as high speed device structures. Several techniques such as direct wafer bonding and separation by implanted oxygen (SIMOX) have been proposed and displayed some level of success. The current techniques, however, do have some limitations. The major drawbacks include difficulty controlling the thickness of the insulating layer and defect generation. A possible solution to these problems is the epitaxial growth of a single crystal insulator on Si followed by epitaxial Si. Epitaxial growth allows for control of both insulating layer thickness and defects as well as crystallographic orientation. Yttrium oxide (Y2O3) is a good candidate for use in such an insulating layer. Y2O3 is lattice matched to Si [a(Y2O3) =1.060 nm and 2a(Si) =1.086 nm], has a high dielectric constant (e=14-18), and is relatively stable at high temperatures. Pulsed laser deposition (PLD) was used to deposit single crystal Y2O3 on Si (111) wafers under UHV conditions. A KrF excimer laser with a wavelength of 248nm was used with substrate growth temperatures ranging from 500°C to 750°C. Epitaxial growth was achieved under all conditions as shown by RHEED, HRTEM, and X-ray diffraction. The films were found to be preferentially Y2O3 (111)//Si (111). Silicon was then deposited on the Y2O3 film via PLD. Growth temperatures for Si deposition ranged from 500°C to 700°C. In situ RHEED and HRTEM showed single crystal Si//Y2O3//Si. Three-dimensional growth was observed at temperatures around 700°C. Reduction of the growth temperature led to mostly 2D growth as indicated by both RHEED and HRTEM. We will report on the conditions for optimal growth of Y2O3//Si and the conditions necessary to obtain 2D growth of epitaxial Si//Y2O3//Si. Structural and electrical characterization of both Y2O3//Si and Si//Y2O3//Si will also be reported.

4:50 PM

In Situ Observation of Epitaxial Co Silicidation on Si(001):
Kunihiro Sakamoto[1]; Tatsuro Maeda[1]; [1]Electrotechnical Laboratory, Electron Devices Div., 1-1-4 Umezono, Tsukuba, Ibaraki 305-8568 Japan

Salicide process forming very thin and yet uniform epitaxial $CoSi_2$ on Si(001) will be a key technology for the formation of contacts in ultra-thin SOI MOSFETs. Conventional salicide process generally forms polycrystalline $CoSi_2$. Recently, methods utilizing reaction control layers have been reported to be able to fabricate epitaxial $CoSi_2$ layers[1]. We observed the formation process of the epitaxial $CoSi_2$ in situ with RHEED and show that oxide on Si(001) surface is an effective reaction control layer that acts as a reaction barrier to Co/Si subsilicide formation and a kinematical barrier to surface migration. A thin oxide layer was formed on Si(001) surface in a hot solution of HCl and H_2O_2. A thin (nominally 1.4nm) Co layer was deposited in a UHV deposition chamber on the Si substrate kept at room-temperature. Subsequent annealing in the UHV chamber was monitored with RHEED. The polycrystalline RHEED pattern from the Co layer after the deposition changed at 550°C to a single-crystalline diffraction from epitaxial $CoSi_2$(001). Since a Co deposition on clean Si(001) surface leads to polycrystalline subsilicide reaction at 350°C, the thin oxide layer thus suppresses Co/Si reaction up to the temperature as high as to form $CoSi_2$ directly without passing subsilicide phases. The c(2x2) structure that characterizes the clean $CoSi_2$(001) surface was not observed since the thin oxide layer originally formed on the Si substrate remained on the epitaxial $CoSi_2$ surface. The c(2x2) structure became visible on elevating temperature up to 750°C. At the same time diffraction from {115} facets and

transmission spots appeared. These results indicates that the facets were grown just after the evaporation of the oxide layer. The surface observed with AFM after the annealing up to 750°C had many rectangular islands of 10-20nm in height, while the surface annealed at 550°C was flat and had no characteristic structure. From these experiments we can say that the surface migration of Co atoms and/or Si atoms, which leads to faceted surface, was suppressed by the surface oxide that stabilized $CoSi_2$ layer. [1] R. T. Tung: Appl. Phys. Lett., Vol. 68, pp3461-3463 (1996).

Session J. Epitaxy for Devices

Thursday AM   Room: Corwin East
July 1, 1999   Location: University Center

Session Chairs: Russell D. Dupuis, University of Texas at Austin, PRO/MEP-R9900, Austin, TX USA; Steven Stockman, Hewlett-Packard Company, San Jose, CA USA

8:20 AM +

DC Characterization of Annealing Effect on the Carbon Doped Base of InGaP/GaAs HBTs Grown by LP-MOCVD: *Qinghong (Jack) Yang*[1]; Dennis W. Scott[1]; Patrick D. Meyer[1]; John Miller[1]; Gregory E. Stillman[1]; [1]University of Illinois, Elect. and Comp. Eng., 208 N. Wright St., Urbana, IL 61801 USA

Carbon is a commonly used dopant in GaAs-based heterojunction bipolar transistors (HBTs) due to its high solubility and low diffusivity. HBTs employing a heavily carbon-doped base have demonstrated excellent gain stability at high current levels. Recent work from our research group has shown degradation of DC curent gain in annealed InGaP/GaAs HBTs due to the formation of carbon precipitates in the base. In this work we demonstrate the direct cause of the gain degradation is recombination in the neutral base. Samples from a single wafer are annealed for 1, 2, 4, and 8 minuets respectively at 600°C which is the growth temperature of the devices. Large area (60 x 60 μm2) HBTs are then fabricated for DC characterization. DC current gain of the devices decreased when the annealing time increases. The Dc current gain is ß=90 at IC = 1 mA for the as grown sample and ß=32 after 8 minutes of annealing. Both forward and reverse characteristics of the base emitter junction are examined for the different annealing conditions. The forward and reverse I-V curves of devices with all annealing conditions are identical. This shows that there is no degradation of base-emitter junction due to annealing, thus, no change in emitter injection efficiency. There is also no change of the base-collector diode behavior due to annealing. Magneto transport measurements are performed on the base of both as grown and annealed devices. The results show that there is no difference in the minority carrier mobility although there is a big variation of gain. This implies the degradation of current gain is due to recombination in the base. Gummel plots for all annealing conditions are also taken, no crossover of IB and IC is observed at low current levels. This indicates there is no significant increase of recombination in the space charge region. The recombination process that degrading the gain must be happening in the neutral base region. There is also almost no change in either the base and the collector ideality factor. This confirms that there is no degradation in the base emitter or the base collector diode. The gain of the devices with different annealing conditions increases with the collector current Ic. This implies the recombination caused by annealing saturates at higher current levels.

8:40 AM

Effect of High-Temperature Annealing on Device Performance of GaInP/GaAs HBTs Grown by LP-MOVPE: F. Brunner[1]; E. Richter[1]; T. Bergunde[1]; *P. Kurpas*[1]; A. Maasdorf[1]; J.W. Tomm[2]; S. Gramlich[1];

I. Rechenberg[1]; S. Kraus[1]; M. Achouche[1]; J. Würfl[1]; M. Weyers[1]; [1]Ferdinand-Braun-Institut fuer Hoechstfrequenztechnik, Mats. Tech. Dept., Rudower Chaussee 5, D-12489 Berlin Germany; [2]Max-Born-Institut fuer Nichtlineare Optik und Kurzzeitspektroskopie, Rudower Chaussee 6, D-12489 Berlin Germany

Heterobipolar transistors (HBTs) for microwave applications require both a high and stable p-type doping (p>1x1019 cm-3) as well as good minority carrier transport characteristics in the GaAs base layer. Carbon is a commonly used p-type dopant due to its low diffusivity and high solubility in GaAs. The incorporation of hydrogen in the MOVPE growth process results in passivation of carbon acceptors. High-temperature annealing steps have been proposed to remove hydrogen from the base and fully activate the carbon doping. We have investigated the effect of high-temperature annealing on GaInP/GaAs HBT device performance. It is shown that even at doping levels of p=2x1019 cm-3 minority carrier properties of carbon-doped GaAs degrade with high-temperature annealing, whereas no significant changes in majority carrier characteristics could be detected. Carbon doping in the range 1x1019 cm-3 to 6x1019 cm-3 was achieved either via TMGa and AsH3 only (intrinsic doping) or using an extrinsic carbon source (CBr4). Spectral and time-resolved photoluminescence as well as cathodoluminescence measurements on single layers were carried out to examine minority carrier properties. The HBT structures were processed both in a fast double-mesa process and a dry-etched power cell process with ledge technology to assess DC device performance. DC characterization results of as-grown HBTs (pbase=3...4x1019 cm-3) reveal a higher current gain for the intrinsic-doped base at low growth temperatures compared to structures containing CBr4 doped layers. Maximum current gains are comparable to the published state-of-the-art. However post-growth annealing at for example 685°C for several minutes causes a current gain reduction of about 50 % for HBTs with a CBr4-doped base layer and 70 % reduction for those with intrinsic base doping. Only small changes in base sheet resistance were observed after annealing, confirming the low hydrogen concentration in the as-grown layers. This is the result of an optimized cool down sequence, which is known to minimize the hydrogen incorporation. Variations of growth parameters such as V/III ratio or growth rate did not improve the thermal stability of the HBTs. HRXRD and Hall measurements on single layers indicate a fully substitutional incorporation of carbon on the As lattice site. SIMS measurements showed complete activation of the carbon acceptors independent of doping method. High-temperature annealing did not result in a decrease in carrier concentration, carrier mobility and lattice mismatch compared with undoped GaAs in the doping range 1x1019 and 6x1019 cm-3. However high-temperature annealing decreases the luminescence intensity of single carbon doped layers indicating the creation of very effective nonradiative recombination centers during this process. High-temperature annealing also results in a reduction of excess carrier lifetime. The exact nature and formation process of the recombination centers is still under investigation.

9:00 AM

Low Resistance Visible Wavelength Distributed Bragg Reflectors: *J. M. Fastenau[1]*; G. Y. Robinson[1]; [1]Colorado State University, Dept. of Elect. & Comp. Eng., Fort Collins, CO 80523 USA

The application of semiconductor heterojunctions, using alloy compositions chosen with small band offset energies, to distributed Bragg reflector (DBR) structures for the purpose of lowering the series resistance is presented. Selecting DBR layer pairs with small valence band or conduction band offsets eliminates the need for complicated structural schemes typically used to smooth out the interface energy barriers, and thus achieves a low resistance DBR using a simple stack of quarter wavelength thick layers. Low resistance, highly reflective DBRs are used in vertical cavity surface emitting lasers (VCSEL). With increasing interest in visible wavelength VCSELs for data storage, laser printers, and plastic optical fibers, we report very low resistance DBRs operating at approximately 650 nm. From theoretical band offset calculations using the Van de Walle model solid theory, heterojunctions of mixed arsenide and phosphide III-V semiconductor lattice-matched alloys were selected to obtain the low band offset DBRs: $Al_{0.14}Ga_{0.38}In_{0.48}P/Al_{0.90}Ga_{0.10}As$ for p-type and $Al_{0.10}Ga_{0.42}In_{0.48}P/AlAs$ for n-type. The specific contact resistance calculations indicated that these alloy compositions should have much lower resistance than the all-phosphide AlGaInP/

AlInP DBRs that previously have been investigated. The epitaxial heterostructures were grown lattice-matched to GaAs substrates by gas-source MBE. Uniformly doped 40-period p-type and n-type DBRs were grown with the calculated AlGaInP/AlGaAs alloy compositions. Using double crystal x-ray diffraction, the DBRs exhibited diffraction spectra typical of very high quality superlattices. Optical measurements indicated a reflectivity exceeding 99% at 637 nm for the p-type DBR and at 656 nm for the n-type DBR. The DBRs were fabricated into test devices and the specific contact resistance was determined using the transmission line method. Measured values of $(2.8\pm1.6)x10^{-4}$ W-cm2 for the p-type DBR and $(2.6\pm2.0)x10^{-5}$ W-cm2 for the n-type DBR were within experimental uncertainty of the theoretical values. These results compare very favorably with resistance values reported for AlGaAs DBRs, regardless of the target wavelength, which employ complicated structural grading schemes designed to lower the stack resistance. On a per period basis, the low valence band offset p-type DBR resistance is $6.9x10^{-6}$ W-cm2/period, which is comparable to the best previous reports [1, 2]. The low conduction band offset n-type DBR resistance is $6.4x10^{-7}$ W-cm2/period, which is an order of magnitude lower than the best previously reported result [2]. Thus, using AlGaInP/AlGaAs heterostructures with optimum alloy compositions, low resistance DBRs with high reflectivity can be obtained at 650 nm without grading the interface composition. [1] S. Chalmers, K. Lear, and K. Killeen, Appl. Phys. Lett. 62, 1585 (1993). [2] M. Peters, B. Thibeault, D. Young, A. Gossard, and L. Coldren, J. Vac. Sci. Tech. B12, 3075 (1994).

9:20 AM

High P-type Doping in InAlP Grown by Metalorganic Chemical Vapor Deposition: *Yuichi Sasajima[1]*; Russell D. Dupuis[1]; [1]The University of Texas at Austin, Microelectronics Research Center, PRC/MER 2.606K-R9950, Austin, TX 78712-1100 USA

InAlP has the largest bandgap of the semiconductors lattice-matched to GaAs, and it is used as a cladding layer in InAlGaP-based short-wavelength optical devices covering the red to yellow spectral range. However, it is difficult to obtain high acceptor concentrations, N_a, for InAlP. This limits device characteristics such as current diffusion in light emitting diodes and the threshold current in laser diodes. There are two factors that suppress N_a in InAlP. First, N_a saturation @1x10^{18}/cm^3 comes from intrinsic properties of InAlP itself. Second, acceptor passivation by hydrogen becomes dominant for Mg and Zn heavy doping. In this work, we studied the Mg and Zn co-doping characteristics for InAlP grown by metalorganic chemical vapor deposition (MOCVD) as well as Mg and Zn doping individually. In order to obtain higher N_a for p-type InAlP, we also investigated chemical potential modulation effects for activation of acceptors, including internal and external potential modulations. The InAlP samples were grown at low-pressure at 650°C in H_2 in an EMCORE GS3200 UTM reactor system using trimethylaluminum, trimethylindium, and PH_3 as sources. Diethylzinc and biscyclopentadienylmagnesium were employed as Zn and Mg dopants, respectively. The free carrier concentration was measured by electrochemical capacitance-voltage profiling, and the In composition was checked by X-ray diffraction rocking curves. Impurity concentrations were estimated by secondary ion mass spectroscopy. Mg and Zn co-doped InAlP showed intermediate doping characteristics between those of Mg- and Zn-doped InAlP, as if reflecting the activation energy difference between Mg and Zn acceptors. However, we have obtained a maximum hole concentration $p_{max}=1.1x10^{18}cm^3$ at 300K for as-grown InAlP:Mg,Zn, compared to $8.7x10^{17}cm^3$ for InAlP:Mg and $1.0x10^{18}cm^3$ for InAlP:Zn. We have also obtained $p_{max}=1.8x10^{18}cm^3$ for ex-situ annealed InAlP:Zn. To our best knowledge, this p_{max} after annealing is the highest value for p-type InAlP grown by MOCVD. The InAlP layer in this sample has an intentional compositional modulation. We believe that a potential modulation formed by the compositional modulation helped the acceptor activation or incorporation. We found two additional properties: (1) p_{max} in InAlP is influenced by the lower and upper layer carrier concentrations. For example, p_{max} in InAlP reaches a maximum value when the lower and upper layers have p_{max} @1x10^{18}cm^3, which is nearly the saturation value. Also, pmax in the upper layer is more critical for acceptor activation, and we measured a larger p_{max} in InAlP with n-type top layer; (2) In incorporation is dependent on the Mg and Zn concentrations, and it also saturates at almost the same conditions as saturated pmax in InAlP. The value $p_{max}=1x10^{18}cm^3$

seems to be a magic number for p-type InAlP. In our talk, substrate off-angle dependence of p_{max} in InAlP will be discussed from the microscopic view of potential modulation including spontaneous ordering.

9:40 AM +

Growth and Characterization of InAlGaP Superlattice Lasers: Yuichi Sasajima[1]; *Richard D. Heller*[1]; Russell D. Dupuis[1]; David A. Kellogg[2]; Nick Holonyak[2]; David T. Mathes[3]; Robert Hull[3]; [1]The University of Texas at Austin, Microelectronics Research Center, PRC/MER 1.606D, Austin, TX 78712-1100 USA; [2]University of Illinois at Urbana-Champaign, Microelectronics Laboratory, 208 North Wright St., Urbana, IL 68101-2991 USA; [3]University of Virginia, Dept. of Mats. Sci. and Eng., Thornton Hall, Charlottesville, VA 22903-2442 USA

InAlGaP-based quaternary materials lattice-matched to GaAs are now widely used for compound semiconductor light-emitting devices, including injection lasers and light-emitting diodes (LEDs). While high-efficiency devices emitting incoherent light in the red, orange, and yellow spectral regions have been demonstrated, injection lasers emitting in the yellow spectral region operating at 300K have not been reported. Fundamentally, the short-wavelength operation of the $In_y(Al_xGa_{1-x})_{1-y}P$ light-emitting materials is limited by the direct-indirect transition at alloy compositions @x=0.55. In order to circumvent this limit, we have explored the use of direct-bandgap InAlGaP alloys incorporated into quantum wells in short-period superlattice (SPSL) heterostructures. The emission wavelength of the recombination radiation of these structures is reduced as a result of the quantum confinement of the electrons and holes in the SPSL. These structures are grown by low-pressure MOCVD in an EMCORE GS3200 UTM reactor system using triethylgallium, trimethylaluminum, trimethylindium, and PH_3 as sources. Growth is carried out at 60 Torr at temperatures @650°C. The lattice matching conditions for the InAlP, InAlGaP and InGaP alloys have been established using X-ray and photoluminescence characterization of @500nm thick layers. The lattice-matched SPSL laser structures were grown on GaAs:Si substrates and consist of the following epitaxial layers: 100 nm GaAs buffer layer, 200-500nm InAlP cladding layer, superlattice active region containing InAlGaP (x=0.7) barriers and InAlGaP wells (0<x<0.3), 200-500nm InAlP cladding layer, GaAs cap layer. The SPSLs are grown simultaneously on (100) GaAs substrates and vicinal (100) wafers with misorientations of 10°, 15° toward <111>A, and <311>B. Growth on the vicinal wafers enhances the disordering of the alloys. We have measured the interface quality of these structures using X-ray diffraction rocking curves, transmission electron microscopy, and 300K photoluminescence (PL). X-ray diffraction measurements and simulation analysis has shown that the superlattice is well formed, as confirmed by the TEM images obtained on several samples. We have found the brightest 300K PL intensity and the narrowest emission linewidth are obtained for SPSLs grown on 15° off wafers. The emission wavelength is also @8nm longer than for 10° off wafers. SPSLs with twenty periods of 1.7nm InGaP quantum wells and 0.9nm InAlGaP (x=0.70) barriers have lased pulsed at wavelengths as short as 604nm (red-orange) under optical excitation at 300K. This laser operation is the strongest yet obtained at this short wavelength. Optical pumping of these samples at 77K has produced lasing at wavelengths as short as 565nm (yellow-green). We have designed strain-modulated aperiodic superlattice heterobarriers to provide increased electron confinement at the heterojunction interfaces. These barriers should permit lasing at higher temperatures for the shorter-wavelength SPSLs. We will report the growth, characterization, and lasing properties of these structures.

10:00 AM   Break

10:20 AM

Device Quality, Bandgap Engineered InAs-Channel Fet Material Structures: *Leye A. Aina*[1]; Harry S. Hier[1]; Anu Mahajan[2]; G. Cueva[2]; Ilesanmi Adesida[2]; Terrance L. Worchesky[3]; Rheanna Riebau[3]; [1]Epitaxial Technologies, LLC, 1450 South Rolling Rd., Baltimore, MD 21227 USA; [2]University of Illinois Urbana Campus, 208 North Wright St., Urbana, IL 61801 USA; [3]University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250 USA

We report the growth of high quality InAs-channel FET material structures on InP using thin buffer layers suitable for device processing. Growth of InAs on InP has the advantage over previous approaches of a lower lattice mismatch between the two materials and therefore should enable the growth of high quality InAs with thinner buffer layers. Material structures for InAs-channel FETs have recently been investigated, because InAs combines the properties of a high electron mobility and saturated electron velocity with the large conduction band discontinuity of its heterojunctions with AlSb and related alloys. These properties are ideal for low noise and low power field effect transistors (FETs) for circuit applications at W-band (94 GHz) and beyond. Because it is impossible to grow semi-insulating InAs substrates and because there is an 8.5% lattice mismatch between InAs, the AlSb buffer layer and GaAs substrates, buffer layers as thick as 2 um have had to be grown to realize high electron mobility InAs FET material structures on GaAs. Thick buffer layers are not suitable for device fabrication because high mesa or deep isolation implants are then necessary for device isolation which can result in high leakage currents and low wafer yields. As a result, InAs FET material structures with device quality electrical properties and structural configurations that lend themselves to high yield circuit processing have yet to be developed. We have grown and characterized InAs-channel FET material structures with thin buffer layers as low as 3000 Å and with electron mobilities as high as 18,650 and 35,900 cm2/volt-sec at 300K and 77K, respectively. The sheet electron concentration for these structures is 2E12 cm-2. We will present detailed data showing that the electrical properties of these materials are the best reported for InAs FET structures grown on thin buffer layers and that InAs-channel FETs with fT and transconductances as high as 158 GHz and 750mS/mm respectively for devices with 0.35 um gate-lengths can be fabricated from these material structures. In addition, we will show that the fTLg figure-of-merit for these InAs-channel FETs is 50.8 GHz.um which is the highest reported for any three-terminal device, raising the possibility of realizing 500 GHz performance with 0.1 um gate-length devices.

10:40 AM

Transport Properties of InAs layers grown on GaP Substrate by MBE: *E. H. Chen*[1]; V. Gopal[2]; E. P. Kvam[2]; J. M. Woodall[1]; [1]Yale University, Dept. of Elect. Eng., New Haven, CT 06520; [2]Purdue University, School of Mats. Eng., W. Lafayette, IN 47907

The growth of high quality InAs epitaxial films has been a continuously researched material for the last decades because of the important technological applications for high-speed electronic devices and opto-electronic devices in the infrared region. However, the lack of semi-insulating InAs substrates has led most studies of the growth of InAs to use substrates such as GaAs, InP, and Si. Recently, direct growth of InAs on GaP by Molecular Beam Epitaxy (MBE) has been successfully demonstrated, despite the large (~11%) lattice mismatch [1]. Cross-sectional Transmission Electron Microscopy (TEM) studies revealed that the misfit strain is accommodated by the generation of a 2-dimensional network of pure edge-type dislocations at the heterointerface and the InAs layer maintains a perfect epitaxial relationship with the GaP substrate. In the present study, Hall effect and electrical resistivity measurements were carried out on InAs films which were grown directly on GaP by Solid Source Molecular Beam Epitaxy. These measurements show the mobility and background carrier density depend on the layer thickness and substrate growth temperature. In common with earlier work for InAs films grown on GaAs or Si, we found that the mobility increases with increasing substrate growth temperature and InAs film thickness. The thickness dependence of the carrier concentration suggests that the InAs/GaP heterointerface is a source of high donor concentration. The high-density dislocations near the heterointerface are the probable sources of these carriers. The temperature dependence of the Hall mobility and carrier concentration has also been examined over the temperature range between 5 to 300 K. An apparent decrease of carrier density from room-temperature is followed by a dip at around 80K and then by a slight increase at lower temperatures. No carrier freeze-out has been observed even at the lowest temperature in our measurement, 5K. These results suggest a finite concentration of the donor band sites reside above the conduction band minimum and the electrons from the donor states will then occupy the lower energy states of the conduction band. The resulting ionized donor centers will

contribute to carrier scattering and the effect on measured mobility will be more prominent at the thinner InAs layer. Nevertheless, high mobilities (> 15,000 cm$_2$/V-sec at 77K) have been achieved on InAs films with 2 mm of thickness. In particular, InAs samples with a 50 A In$_{0.8}$Al$_{0.2}$As cap layer showed a dramatic increase in mobility compared to the similar samples grown without any passive layer. We believe this In$_{0.8}$Al$_{0.2}$As layer can effectively eliminate the surface electron accumulation layer caused by the Fermi level pinning on the InAs free surface.[1] J.C.P. Chang, T.P. Chin, and J.M. Woodall, Appl. Phys. Lett., 69,981,1996.

11:00 AM
Effects of HEMT Pseudomorphic Channel Material Design on Device Performance: *Yaochung Chen*[1]; Richard Lai[1]; Mike Wojtowicz[1]; Mike Barsky[1]; Ronald Grundbacher[1]; T. P. Chin[1]; Dwight C. Streit[1]; [1]TRW, Inc., Electr. & Tech. Div., One Space Park, D1/1050, Redondo Beach, CA 90278 USA

We have investigated and optimized the pseudomorphic channel material designs for both GaAs- and InP-based HEMTs. As a result, we have demonstrated word record low noise and power performance from both types of devices covering frequencies ranging from 2 to 200 GHz. In this work, we present the effects of pseudomorphic channel material design on device performance. Various channel designs are discussed. The key variable in optimizing HEMT performance is the In composition in the InGaAs channel. High In composition is desired since it reduces electron effective mass and increases mobility and saturation velocity and, thus, improves device gain and cutoff frequency. However, excess In introduces compressive strain. Therefore, channel design involves trade-off between the advantages brought by the excess In and the disadvantages brought by strain. Our uniform channel designs have an InGaAs layer with constant In composition sandwiched between AlGaAs or InAlAs buffer and Schottky layers. In these structures, electron mobility increases initially as In composition increases but shows a reversal when In reaches ~25% higher than lattice-matched. The reversal in mobility is due to the fact that one needs to reduce channel layer thickness to remain pseudomorphic. A thin channel increases the electron wavefunction penetration into the low mobility buffer and Schottky barrier layer, which results in increased interface scattering. Furthermore, the first subband energy in a thin channel is pushed up, which results in poor electron confinement. In a stepped channel design, a GaAs layer is inserted between the AlGaAs buffer and the InGaAs channel for the GaAs HEMT, and an InGaAs layer with lower In composition is inserted between InAlAs buffer and InGaAs channel for the InP HEMT. These designs show higher electron mobility by reducing buffer-channel interface scattering and lowering the first sub-band energy. For a double-doped power HEMT structure, the stepped channel design moves the back doping plane farther away from the gate metal and may reduce device gain. Therefore, the stepped channel thickness needs to be carefully optimized. We have also investigated stepped channel InP HEMT with tensile strained InGaAs insert. The tensile strain in the insert balances the compressive strain in the channel and can potentially increase the critical thickness of the channel InGaAs layer. However, mobility degrades dramatically when the buffer indium composition reduces below 42%. Our graded channel HEMT design has a single quantum well with In composition graded from 60 to 80%. This structure combines the advantages of the uniform and stepped channel designs. We have demonstrated 305 GHz cutoff frequency[1] and the first ever 190 GHz LNA with 7.2 dB gain[2] using this structure. High breakdown voltage is desired for high power applications. Device breakdown voltage reduces as channel In composition increases. Therefore, for InP-based HEMT, we have used double-doped structure with lattice-matched InGaAs channel to achieve high current carrying capability, high transconductance, and high breakdown. A HEMT MMIC amplifier fabricated on this structure with 0.15 mm gate demonstrated a world record 427 mW output power and 19% power-added-efficiency at 95 GHz[3]. To further advance the W-band power performance, we have developed a composite channel InP-InGaAs channel design. We have shown that the composite channel design can significantly improve device on-state and off-state breakdown without degrading RF performance. [1] M Wojtowicz, et al. IEEE Electron Device Lett. Vol. 15, No. 11, 1994, p. 477. [2] R. Lai, et al., Microwave and Guided Wave Lett., Vol. 8, no. 11, 1998, p. 393. [3] Y.

C. Chen, et al., Microwave and Guided Wave Lett., Vol. 8, no. 11, 1998, pp. 399.

11:20 AM
Growth of High-Performance InP IMPATT Diodes by Metalorganic Chemical Vapor Deposition: *Ho-Ki Kwon*[1]; Joongseo Park[1]; Russell D. Dupuis[1]; James W. McClymonds[2]; Michael J. Welch[2]; [1]The University of Texas at Austin, Microelectronics Research Center, MRC/MER - R9900, Austin, TX 78712-1100 USA; [2]Raytheon Electronic Systems, 131 Spring St., Lexington, MA 02173 USA

Impact avalanche transit time (IMPATT) diodes are important elements in high-power, high-frequency microwave systems. In the past, most III-V compound semiconductor IMPATT devices have been produced from GaAs-based materials grown by hydride vapor-phase epitaxy (VPE). The use of InP for IMPATT diodes is expected to greatly increase the maximum frequency of oscillation due to the increased electron mobility relative to GaAs. We report the growth and characterization of single- and double-drift InP IMPATT structures and the characterization of devices fabricated from these materials. The IMPATT structures are grown by low-pressure MOCVD in an EMCORE GS 3200 reactor in a H$_2$ ambient using triethylgallium, trimethylindium, arsine and phosphine sources. The typical double-drift IMPATT structure consists of nine epitaxial layers including n-type and a p-type "delta doped" layers and n- and p-type lightly doped "drift" layers. The avalanche layer is not intentionally doped. The double-drift IMPATT structures consist of p$^+$ p$^-$ I n$^-$ n$^+$ layers of InP with a p$^+$ InGaAs cap layer for contacting. This structure places severe requirements upon the switching of dopants during the growth process and the control of background doping concentrations. We have explored the use of diethylzinc (DEZn) for p-type doping and Si$_2$H$_6$ and tetraethyltin (TESn) for n-type doping. Our initial devices employing only Zn and Sn dopants were limited by the transient behavior of the TESn source. However, it is difficult to control Si doping at the low concentrations required for the "drift" layer using diluted mixtures of disilane. We have found that improved device profiles can be obtained by using Sn for the lightly doped "n-drift region" and Si for the "n-spike region". DEZn is used for the growth of the "p-drift region", "p-spike" and "p-contact" layers. The doping changes abruptly from n=2-10x10^{15} cm^{-3} for the n-drift region to n=2-4x10^{17} cm^{-3} for the n-spike. The p-spike is grown with p=2x10^{17} cm^{-3} and the p-drift is doped to p=1x10^{16} cm^{-3}. These requirements place severe demands upon the control of the doping and total charge in the spike layers. We have developed a growth process that can produce abrupt doping profiles. We will report also on the performance of InP IMPATT diodes. Our initial InP IMPATT devices have been measured to provide 2.2W at 12.6% efficiency at 34GHz under pulsed operation using a 300 ns pulse width with a 10% duty cycle. These initial devices were limited by a processing problem and we expect significant improvement in the "reprocessed" material and also from subsequently grown InP IMPATT wafers having improved doping profiles. We believe that these results may be the first demonstrated high-performance InP-based IMPATTs.

11:40 AM Late News

Session K. Nanoscale Characterization

Thursday AM   Room: Corwin West
July 1, 1999   Location: University Center

Session Chairs: Julia Hsu, University of Virginia, Charlottesville, VA USA; Edward Yu, University of California, San Diego, CA USA

8:20 AM +
Nanoscale Charge Transport Properties of Co/SiO$_2$ Multilayer Structures and Their Application in a Novel Magnetic Field

Sensor: *Daniel M. Schaadt*[1]; Edward T. Yu[1]; Sandra Sankar[2]; Ami E. Berkowitz[2]; [1]University of California at San Diego, Dept. of Elect. and Comp. Eng., 9500 Gilman Dr., La Jolla, CA 92093-0407 USA; [2]University of California at San Diego, Dept. of Phys., Center for Magnetic Recording Research, 9500 Gilman Dr., La Jolla, CA 92093-0401 USA

Discontinuous magnetic metal/insulator multilayers are of current interest for application as magnetoresistive elements in magnetic field sensors due to their sharp magnetoresistance at room-temperature, low saturation field, and high mechanical and chemical stability due to the separation of magnetic particles by the insulating matrix. Realization and optimization of magnetic field sensor devices based on these materials requires detailed characterization and understanding of electrical transport properties at the nanometerscale. We have used scanning force microscopy to study localized charge injection and subsequent charge transport in Co/SiO_2 multilayers. Samples were prepared by co- or alternating sputtering of Co and SiO_2, respectively, on Si substrates. Previous transmission electron microscopy studies have shown that Co layers fabricated in this manner are discontinuous, resulting in the formation of Co nanoclusters embedded in SiO_2. Charge was injected into and removed from the Co nanoclusters in a highly localized manner by applying a bias voltage pulse between a conducting proximal probe tip and the Co/SiO_2 multilayers sample. Electrostatic force microscopy was used to image charged areas, to determine quantitatively the amount of stored charge, and to characterize charge transport within the Co layer and into the Si substrate. Charge was deposited controllably and reproducibly within areas ~20-50 nm in radius, and an exponential decay in the peak charge density was observed with decay times on the order of several minutes. Longer decay times were measured for positive than for negative charge with the ratio of the decay times depending on the nominal Co film thickness. These results are interpreted as a consequence of the Coulomb-blockade energy associated with single-electron charging of the Co nanoclusters. These observations have significant implications on application of such films in magnetic field sensors for data storage systems, where high-frequency response is required. In addition, techniques such as nanoscale patterning and increasing SiO_2 layer thicknesses for suppressing discharging and consequently improving charge retention times have been investigated. Based on the observation of charge storage in the magnetoresistive Co layer, a novel monolithic transistor-amplified magnetic field sensor has been demonstrated. In this device structure, a magnetoresistive layer is incorporated within the gate of a Si MOSFET. Applying or changing an external magnetic field results in a change in current flow through the magnetoresistive layer and thus in a change in charge density in the gate. This change in charge density yields a threshold voltage shift in the transistor, leading to an amplification of the response to the applied magnetic field.

8:40 AM

Novel Application of Kelvin Force Microscopy: *Rafi Shikler*[1]; Tamir Meoded[1]; Norbert Fried[1]; Nurit Ashkenasy[1]; Yossi Rosenwaks[1]; [1]Tel-Aviv University, Faculty of Electr. Eng., Dept. of Phys. Electr., Ramat-Aviv, Tel-Aviv 69978 Israel

Scanning probe microscopy has opened new opportunities to image semiconductor surfaces with unprecedented spatial resolution. Perhaps the most widely used scanning probe instrument is the atomic force microscope (AFM), which provides direct surface topographic images, as well as information on other tip/sample forces like friction, magnetic, and electrostatic. The Kelvin force microscopy (KFM) technique has already been demonstrated as a powerful tool for measuring electrostatic forces and electric potential distribution with nanometer resolution; it has found many diverse applications in recent years. In this work we present two additional applications of the KFM technique recently demonstrated by our group. The first is the use of the KFM for a direct measurement of surface minority carrier diffusion lengths. The method is based on measuring the surface photovoltage between the KFM tip and the surface of a uniformly illuminated semiconductor junction. The photogenerated minority carriers diffuse to the junction and change the contact potential difference (CPD) between the tip and the sample, as a function of the distance from the junction. The diffusion length, L, is then obtained by fitting the measured photovoltage using the minority carrier continuity equation. The method is applied to measurements of electron and hole diffusion lengths in GaP epilayers;

values of L in the surface space charge regions have been obtained. The second application we present is the measurement of electronic defects and local Fermi level pinning at a semiconductor surface. We have measured the CPD and the surface photovoltage on the surface of a GaP single crystal. The measurements show that under super bandgap illumination, there are regions at the semiconductor surface where the induced surface photovoltage is close to zero. The results are analyzed using a 2-D solution of Poisson equation and interpreted in terms of spatial distribution of surface states and recombination centers.

9:00 AM +

InGaAs/InP Quantum Well Intermixing Studied by Cross-Sectional Scanning Tunneling Microscopy: *Huajie Chen*[1]; Randall M. Feenstra[1]; P. G. Piva[2]; I. V. Mitchell[2]; R. D. Goldberg[3]; G. C. Aers[4]; P. J. Poole[4]; S. Charbonneau[4]; [1]Carnegie Mellon University, Dept. of Phys., Pittsburgh, PA 15213; [2]University of Western Ontario, Dept. of Phys. and Astronomy, London N6A3k7 Canada; [3]University of Salford, Joule Laboratory, Dept. of Phys., Salford M5 4WT UK; [4]National Research Council of Canada, Institute for Microstructural Sciences, Ottawa K1A0R6 Canada

The Dr. toward fully integrated photonic devices of quantum well (QW) type requires improved techniques for QW bandgap Eng.. In this work, cross-sectional scanning tunneling microscopy (STM) has been used to study InGaAs/InP QW intermixing produced by phosphorus implantation followed by thermal annealing. The increased width of the QW after intermixing is directly measured by STM images. The strain development after intermixing is studied in detail, and a tentative model is proposed to explain the experimental results. Two different kinds of samples have been studied, each consists of 20 periods nominally lattice-matched InGaAs quantum well and InP barrier. Sample A has a 10 nm InP cap layer and P ions are implanted through the QW stack; sample B has a 1500 nm InP cap layer and P ions are implanted into the cap layer in front of the QWs. Following anneal both samples display PL blueshift. Cross sectional STM shows a broadening of the individual QWs, by 1.6nm (sample A) and 1.9 nm (sample B). More importantly, significant strain has developed in sample B following intermixing, the well becomes tensilely strained and the interface of well and barrier becomes compressively strained, which can only result from an enhanced group V over group III intermixing. On the contrary, sample A reveals no such strain contrast. Finite element computation is used to determine the group V to group III interdiffusion length ratio. This result is explained based on the different types of defects responsible for the intermixing, namely, both group V and group III defects attribute roughly equally to the intermixing in sample A, whereas mostly group V defects induced intermixing on the group V sublattice in sample B. This work was supported by a grant from NSF.

9:20 AM

Ordering-Induced Band Structure Effects in GaInP Studied by Ballistic Electron Emission Spectroscopy: *Michael Kozhevnikov*[1]; Venkatesh Narayanamurty[1]; Yong Zhang[2]; Angelo Mascarenhas[2]; Jerry Olson[2]; [1]Harvard University, Gordon McKay Laboratory, 9 Oxford St., Cambridge, MA 02138 USA; [2]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

Ordering induced changes in the band structure of $GaInP_2$ are important for its application in advanced solar cells with very high conversion efficiency, for potential band-gap engineering and for fundamental studies of atomic ordering. To characterize the structural and electronic properties of $GaInP_2$, we have used the Ballistic Electron Emission Microscopy (BEEM) technique which allows the study of buried heterostructures with high spatial resolution (~ few nm) [1]. To make the most out of the BEEM capabilities, this work has detailed a quantitative study of the second voltage derivative (SD) of the ballistic electron emission spectra. In our recent study of GaAs/AlGaAs heterostructures [2], the SD-BEEM spectroscopy was shown to be very informative, since the SD-BEEM spectrum is proportional to the heterostructure transmission coefficient, and, therefore, allows an explicit energetic partitioning of the transport channels. Then, we associate two peaks observed in the SD-BEEM spectra of disordered $GaInP_2$ on n^+ GaAs substrate with the G and L conduction minima, whereas an additional third peak in the SD-BEEM spectra of ordered $GaInP_2$ we associate with the L-band splitting due to the ordering-induced "fold-

ing" of one (from four) L valley onto the G point. According to our results, this splitting is @ 0.1meV. Additional indication of the effect of the ordering is the experimentally observed reduction of the effective threshold for ordered GaInP₂ samples comparing to disordered samples. Since the BEES technique allows us to study independently the conduction and valence band offsets of buried heterostructures, we find that the ordering-induced bandgap reduction is accommodated mostly in the valence band alignment between GaAs and GaInP₂. In addition, the BEEM images of ordered GaInP₂ samples show regions of enhanced and reduced current on the scale of ~0.5 mm, and we relate this BEEM contrast regions to be due to the order parameter fluctuations or antiphase domain boundaries. [1] for review, see e.g. V. Narayanamurti, Sci. Rep. RITU A44, 165 (1997). [2] M. Kozhevnikov, V. Narayanamurti, C. Zheng, Y. Chiu and D. Smith, accepted for publication in Phys. Rev. Lett. This work is supported by NSF Grant # ECS 9531133 and NREL contract #XCR-6-16770

9:40 AM   Late News

10:00 AM   Break

10:20 AM   +
Nanoscale Characterization of Stresses in Semiconductor Devices: *James John Demarest[1]*; Robert Hull[1]; Kathryn Schonenberg[2]; Koenraad Janssens[3]; [1]University of Virginia, Mats. Sci. and Eng., Thornton Hall, McCormick Rd., Charlottesville, VA 22903 USA; [2]International Business Machines Corporation, IBM Research Div./SRDC, Hudson Valley Research Park, 1580 Rt. 52, B/640, M/S AE1, Hopewell Junction, NY 12533 USA; [3]OCAS, The Research Centre of the Sidmar Group, J.F. Kennedylaan 3, B-9060, Zelzate Belgium

By using transmission electron microscopy (TEM) and focused ion beam (FIB) technology in conjunction with an ensemble of Computer programs which include finite element modeling (FEM), electron diffraction strain contrast simulation, and image manipulation we have been able to quantitatively measure stresses in semiconductor devices with a spatial resolution on the order of nanometers and a sensitivity on the order of tens of Mega Pascals. By utilizing this technique upon silicon germanium (SiGe) heterojunction bipolar transistors (HBTs) fabricated by IBM, stress information on an extraordinarily high level of resolution and sensitivity allows insight into the structural features (e.g. isolation trenches) and elemental composition (epitaxially grown SiGe base). This technique thus allows valuable knowledge about device design for low defect density prior to fabrication, as well as measurement of stresses in real devices once they have been created. The stress measurement process consists of first obtaining a sample by FIB sputtering which results in a thin cross sectional membrane of known geometry through the HBT. This geometrical information is critical for later quantitative applications of electron diffraction equations to the theoretical stress field resulting from FEM. An experimental image obtained via TEM is then used to build a finite element structure with ANSYS software. FEM is then used to obtain a theoretical stress field throughout the HBT of the actual thin membrane structure, where the intrinsic stresses of polycrystalline and amorphous materials contained within the device structure were determined by wafer curvature measurements. A program which simulates electron diffraction contrast (SIMCON) from FEM stress field data by the application of the dynamic electron diffraction Howie-Whelan Equations is then used to create a simulated TEM image. The two images, experimental and theoretical, are then normalized to each other such that their intensities and gray levels fall along the same dynamic range. Subtraction of one image from the other on a pixel by pixel basis can then be performed, which creates a difference map of changes in grayscale. Once the stress sensitivity per gray level is determined, it becomes possible to quantify the stresses in the experimental structure by using the theoretical model as a starting point. Areas of higher stress within the device structure have been identified. These include single crystalline regions in close proximity to tungsten (W) vias (due to the large intrinsic stress present in W-on the order of 1.2 GPa), material immediately adjacent to thin thermal SiO2 layers, the strained SiGe epitaxial base, and oxide trenches.

10:40 AM
Extending Lateral Composition Modulations in InAs/AlAs Superlattices with Miscut Substrates: *David M. Follstaedt[1]*; Andrew G. Norman[2]; S. Phil Ahrenkiel[2]; John L. Reno[1]; Steve R. Lee[1]; Eric D. Jones[1]; Joanna Mirecki Millunchick[3]; Angelo Mascarenhas[2]; Yong Zhang[2]; Ray D. Twesten[4]; [1]Sandia National Laboratories, Dept. 1112, Mail Stop 1056, Albuquerque, NM 87185-1056 USA; [2]National Renewable Energy Laboratory, Golden, CO 80401-2163 USA; [3]University of Michigan, Mats. Sci. and Eng., Ann Arbor, MI 48109-2163 USA; [4]University of Illinois, Center for Microanalysis, Urbana, IL 61801-2985 USA

The microstructure of composition modulation in (InAs)n/(AlAs)m short-period superlattices grown on (001) InP has been well characterized. For optimum growth conditions (n @ m = 0.5 - 2.0, Tgro ³ 530°C), the laterally modulated regions grow as vertical columns with only short extension in the growth plane (<~0.1 mm). Moreover, the lateral modulation occurs equally along two directions in the growth plane; for superlattices grown with moderate average tensile strain (< 0.4% in-plane strain), these are [130] and [310]. We have also found that the composition variations produced in these alloys are quite large: local enrichments in In concentration up to In76Al24As have been determined. Recently, we have shown that such composition modulation produces large reductions in photoluminescence energy, up to 0.5 eV relative to that expected for a random alloy of the same average composition (ie, reduced from 1.5 to 1.0 eV). The size of the reduction tracks the amplitude of the modulations as measured by x-ray diffraction. Moreover, these large bandgap reductions are consistent with the measured compositional enrichments. However, the rather complex microstructure of (InAs)n/(AlAs)m limits the development and study of the novel electronic properties expected for composition modulation. With the intent of producing extended modulations in the growth plane that are along one direction only, we are examining growth on miscut substrates. A superlattice was grown in slight tension on a substrate miscut 2° from [001] toward [101]. This surface has a lateral component of its normal that is 18° from the [310] modulation direction but is 72° from [130]. TEM and x-ray diffraction indicate that strong modulation is present, but with the modulation in the [310] direction predominating. Furthermore, the modulated segments are longer, extending 0.2 - 0.3 mm in the growth plane. Thus growth on miscut substrates is producing more nearly ideal modulation geometries and microstructures for studies of electronic properties. Our results suggest that surface steps may play an important role in determining the in-plane organization of modulated regions. Properly miscut surfaces may lead to modulated structures that confine carriers to a single set of InAs-rich planar regions that are £10 nm thick. Other orientations are being examined to learn how the miscut determines the microstructure of composition modulation.

11:00 AM   +
Non-Alloyed Ohmic Contact on GaAs at Nanometer Scale: *Takhee Lee[1]*; B. L. Walsh[3]; D. B. Janes[3]; E. H. Chen[3]; Jia Liu[2]; J. M. Woodall[3]; M. R. Melloch[3]; R. P. Andres[2]; R. Reifenberger[1]; [1]Purdue University, Dept. of Phys., W. Lafayette, IN 47907 USA; [2]Purdue University, School of Chem. Eng., W. Lafayette, IN 47907; [3]Purdue University, School of Elect. and Comp. Eng., W. Lafayette, IN 47907 USA

Even though prototype electronic devices have shrunk into the nanometer-scale range, the contacts to nano-devices often have dimensions of order 1 mm or greater. Thus, the contacts still require 10²-10⁴ greater area than the active nano-devices. The demands on ohmic contacts at the nanometer scale are quite stringent and present significant problems for any approach based on an alloying process.[1] As reported earlier, non-alloyed ohmic contacts may be appropriate for nano-device applications since they are free from a deep interface and they possess spatial uniformity.[2] These non-alloyed contacts employ low-temperature grown GaAs (LTG:GaAs), i.e. GaAs grown at a temperature of 250-300°C by molecular beam epitaxy.[3] We have previously shown that ohmic nano-contacts can be formed to n-GaAs device layers using this non-alloyed ohmic contact approach.[2] In this presentation, we extend the previous work to the development and characterization of high performance nano-contacts to n-GaAs using both n-type and p-type LTG:GaAs caplayers. The controlled-geom-

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etry nano-contact was obtained by depositing a 4 nm single crystalline Au cluster on an ohmic contact structure with a chemically stable LTG:GaAs surface layer using ex-situ chemical self-assembly techniques. A self-assembled monolayer of xylyl dithiol ($C_8H_{10}S_2$; denoted as XYL) was used to provide mechanical and electronic tethering of the Au cluster to the LTG:GaAs surface. The dimensions of the Au cluster determine the size of the nano-contact. The electrical characteristics of the Au cluster/XYL/GaAs were determined using UHV scanning tunneling microscopy (STM). It has been found that the cluster/XYL contact to samples with both n-type and p-type LTG:GaAs provide an effective ohmic nano-contact with good repeatability between various clusters distributed on the surface. STM current-voltage spectroscopy for these nano-structures provide estimates for the specific contact resistance and current density of the nano-contacts. For the case of an n-type LTG:GaAs caplayer, a contact resistance of 1×10^{-6} W cm^2 and a current density, 1×10^6 A/cm^2 have been measured. When a p-type LTG:GaAs caplayer is used, the corresponding values are 1×10^{-7} W cm^2 and 1×10^7 A/cm^2, respectively. These contact properties are comparable to those observed in high quality large area ohmic contacts to n-type GaAs.[3] A model explaining the origin of the ohmic contact as well as the difference in the contact properties between the samples with the n-type and p-type caplayers will be presented. Possible applications for these nano-contacts will also be discussed. [1] A. G. Baca, et al., Thin Solid Films 308-309, 599 (1997). [2] Takhee Lee, et al., submitted to Appl. Phys. Lett.[3] M. P. Patkar, et al., Appl. Phys. Lett. 66, 1412 (1995).

11:20 AM
Nanomagnetic and Superconducting Properties of Self-assembled Quantum Dots: *Supriyo Bandyopadhyay*[1]; Latika Menon[1]; Seema Nair[1]; Hou Zheng[2]; David J. Sellmyer[2]; [1]University of Nebraska, Dept. of Elect. Eng., Lincoln, NE 68588-0511 USA; [2]University of Nebraska, Dept. of Phys., Lincoln, NE 68588-0111 USA

Regimented arrays of cylindrical ferromagnetic quantum dots with average diameter of 10 nm and heights ranging from 10-100 nm have been self-assembled by electrodepositing cobalt into self-organized pores in anodized alumina. The magnetic properties of these dots show interesting dependences on a number of parameters such as the height of the dots, the ac frequency at which the electrodeposition is carried out and the amplitude of the ac voltage used. We found that there are optimum ranges for these parameters to obtain the best magnetic properties. For instance, the magnetization of the dots nearly disappears if the ac voltage has an rms amplitude less than 12 V or the frequency is less than 50 Hz. The magnetization again deteriorates past a frequency of 300 Hz. Some of these results can be qualitatively explained in terms of the magnetocrystalline anisotropy of cobalt and the relative orientation of the c-axis with respect to the long axis. We are carrying out HREM analysis to confirm these conclusions. We have measured the magnetic coercivity and remanence ratio of the cobalt quantum dots and found a coercivity of 2.4 kOe, which, to our knowledge, is the highest reported to date. The remanence ratio is also very high (> 0.75). This is a rich system to study the interaction between the magnetic grains and magnetization reversal mechanisms by varying the dot size and interdot separation. They also offer a realistic hope of realizing ultra dense thermally stable magnetic storage media with a bit density exceeding 100 Gbits/sq-inch. A number of other materials such as nickel and iron have also been fashioned into quantum dot arrays, but their properties are inferior to those of cobalt. Lead quantum dots have been produced by the same self-assembly technique and their superconducting properties have been studied by extensive SQUID measurements. This is an ongoing investigation. In these systems, the dot size is smaller than the bulk coherence length of Cooper pairs so that there is a drastic confinement of the order parameter and a clear possibility of type I to type II transition. Initial measurements seem to show a significant increase in the transition temperature and critical magnetic field. A series of experiments are now underway to establish the origins of these increases. We will report on the magnetic and superconducting properties of the above self-assembled quantum dots and demonstrate their usefulness in synthesizing a number of magnetic and superconducting devices.

Session L. Wide Bandgap AlGaN/ GaN Heterostructures

Thursday AM   Room: Lotte Lehman Hall
July 1, 1999   Location: Music Building

Session Chairs: Ilesanmi Adesida, University of Illinois-Urbana, Urbana-Champaign, IL USA; Umesh Mishra, University of California, ECE Dept., Santa Barbara, CA USA

8:20 AM
Stress/Strain during MOCVD of AlGaN/GaN on LT GaN/AlN Buffers: *Jung Han*[1]; Jeff J. Figiel[1]; Sean J. Hearne[1]; Jerry A. Floro[1]; Steve R. Lee[1]; [1]Sandia National Laboratories, MS-0601, P.O. Box 5800, Albuquerque, NM 87185-0601 USA

(Al, Ga)N family has been a subject of intense study for their applications in optoelectronic and electronic devices. This material system, however, exhibits a tendency of cracking as film thickness or Al content exceeds certain critical limits. As-grown (Al, Ga)N films are often found to be strained as determined by ex-situ characterizations such as x-ray diffraction, wafer curvature, PL and Raman measurements. Several mechanisms could contribute to the occurrence of strain: (i) a large mismatch (2.4%) in the in-plane lattice constants exists between AlN and GaN, (ii) growth of (Al,Ga)N often takes place at high growth temperatures (> 1000°C) on non-native substrates with substantial mismatches in thermal expansion coefficients, and (iii) the employment of multi-step nucleation procedures on low temperature (LT) buffer layers with complex proceedings of growth evolution. Most ex-situ, post growth strain characterizations measure a compounded effect from all three mechanisms. In the case of growth on sa pphire substrates, the tensile contributions from items (i) and possibly (iii) are often masked by the compressive component (ii) due to a thermal expansion mismatch. Several characterization techniques were employed in this work in order to attain a coherent view among issues such as grown-in stress, morphological evolution, and final structural quality. An in-situ wafer-curvature-based monitor was used to extract information of thin-film stress during MOCVD growth. Specular optical reflectance was employed for morphological (on the optical scale) evolution. Both the structural quality and thin film stress were examined using high-resolution x-ray diffraction and grazing-incidence diffraction along [0002] and [101-0] directions. In a comparative study of GaN and AlN buffers, we found that both buffer schemes are capable of supporting subsequent high temperature (HT) GaN growth resulting in final rocking-curve linewidth of around 360" for both [0002] and [101-0] diffraction. Depending on the LT buffer layers employed, nevertheless, HT GaN films can nucleate and grow under either a tensile (using a LT GaN buffer) or compressive condition (using a LT AlN buffer). In-situ reflectance indicates that the degree of initial 3-D islanding during morphological evolution does not significantly change the magnitude and sign of the grown-in stress. Origin of the tension for GaN on LT GaN is not known, possibly due to the in-plane lattice mismatch between LT and HT GaN, which tends to exert a tensile strain to the HT GaN. The compressive stress for GaN grown on LT AlN probably reflects the mismatch between AlN and GaN. Preliminary investigation suggests that AlGaN growth exhibits a similar trend. The correlation between structural quality an d film stress will also be presented. Sandia is a multiprogram laboratory, operated by Sandia Corporation, a Lockheed Martin company, for the United States Dept. of Energy, under contract DE-AC04-94AL85000.

8:40 AM +

Local Electronic Structure of AlGaN/GaN Heterostructures Probed by Scanning Capacitance Microscopy: *Kurt V. Smith*[1]; Ed T. Yu[1]; J. M. Redwing[2]; K. S. Boutros[2]; [1]University of California, San Diego, Elect. and Comp. Eng., 9500 Gilman Dr. 0407, La Jolla, CA 92093 USA; [2]ATMI/Epitronics

III-V nitride semiconductor heterostructures are of interest for a wide range of applications including visible light emitters, visible-blind ultraviolet photodetectors, and high-temperature, high-power transistors and diodes. The presence of high defect densities in typical nitride semiconductor material, combined with the strong coupling between structure, composition, and electronic properties via spontaneous and piezoelectric polarization effects, make detailed characterization and understanding of local structure and electronic properties essential in nitride heterostructure materials and device Engineering. We have used atomic force microscopy (AFM) and scanning capacitance microscopy (SCM) to characterize structural morphology and local electronic properties in GaN/AlGaN heterostructure field-effect transistor (HFET) epitaxial layer structures. The samples were grown by metalorganic chemical vapor deposition (MOCVD) on sapphire substrates. The epitaxial layers consisted of a buffer layer followed by 3μm of GaN, capped by 300A $Al_{0.25}Ga_{0.75}N$. All layers were nominally undoped. It has, however, been well established that spontaneous and piezoelectric polarization effects lead to the formation of a two-dimensional electron gas (2DEG) at the GaN/AlGaN interface with high sheet carrier density that is strongly dependent on the Al concentration in the barrier layer. AFM images of the AlGaN surface reveal the presence of atomic steps and a surface structure similar to that of MOCVD-grown GaN surfaces. Detailed SCM images have been obtained for sample bias voltages ranging from ?6 V to 6 V, allowing features in local electronic structure to be resolved both laterally and in depth. Local variations in the charge distribution create changes in the local C-V characteristics, which can be observed as voltage-dependent contrast in SCM images. At large positive sample bias voltages, for which the 2DEG is depleted and the depletion edge is within the GaN layer, relatively little contrast is observed. As the sample bias voltage is decreased, contrast associated with local variations in the threshold voltage for formation of the 2DEG is observed, with lateral variations present at length scales ranging from ~0.1μm to >1μm. Certain features observed in the SCM images appear to be correlated with features in surface morphology, while others show little or no correlation with surf ace structure. An approximate analysis suggests that local variations in threshold voltage of ~1V are present. As the sample bias voltage is further decreased to large negative values, features that appear to be associated with surface electronic structure become more apparent in the SCM images. SCM images obtained at increasingly negative sample bias voltages exhibit contrast inversion compared to those obtained at voltages corresponding to formation of the 2DEG, as would be expected for contrast arising from local variations in sheet charge density. Possible sources of the observed local variations in electronic properties, including variation in composition, layer thicknesses, and local defect structure, have been investigated.

9:00 AM

Polarization Fields in AlGaN/GaN Heterojunctions: *James Paul Ibbetson*[1]; [1]University of California, ECE Dept., Santa Barbara, CA 93106

Recently it has become clear that interface charges induced by spontaneous and piezoelectric polarization are very important in determining the band profile in group-III nitride heterostructures. Here we report on the direct measurement of the polarization field strength in $Al_xGa_{1-x}N$/GaN heterostructures with Al content in the range $0.15<x<0.35$, such as is typically used in nitride HFET's. The experiment involves capacitance-voltage (C-V) and current-voltage (I-V) measurements on symmetric GaN/AlGaN/GaN structures[1] grown by MOCVD. The GaN cladding layers were lightly n-doped, while the thin (10 – 30 nm) AlGaN barrier was nominally undoped. Diodes were fabricated by making separate Ohmic contacts to the top and bottom n-GaN layers. As expected in the presence of polarization-induced sheet charges at the upper and lower heterointerfaces the I-V and C-V characteristics were strongly asymmetric with respect to the polarity

of the applied bias. Results near zero bias were consistent with an electron accumulation layer at the lower interface and a depletion layer in the GaN above the upper interface. Applying a sufficiently large negative bias to the top contact (the exact bias being dependent on the barrier Al content and thickness) reversed the situation. By extracting a polarization-induced interface charge from the C-V curves, we found that the apparent charge was up to 50% smaller than expected based on theoretical values in the literature. Possible explanations include (i) compensating interface charge that partially screens the large (~106 V/cm) polarization fields in these materials and/or (ii) a high density (>1018 cm-3) of unintentional donors in the AlGaN barrier. More definitive experiments are in progress but it is worth noting that the latter explanation could help explain the 1013 cm-2 2DEG electrons typically observed in undoped AlGaN/GaN HFET's. [1] See for example, Figure 2: Measured I-V and C-V curves for a n-GaN/AlGaN/n-GaN structure.

9:20 AM +

Surface Potential Effects Due to the Piezoelectric Charge Associated with Dislocations in GaN: *Changchun Shi*[1]; Peter M. Asbeck[2]; Edward T. Yu[2]; [1]University of California, San Diego, Dept. of Phys., 9138-I, Regents Rd., La Jolla, CA 92037; [2]University of California, San Diego, Dept. of Elect. and Comp. Eng., La Jolla, CA 92037

Wurtzite GaN and nitride semiconductor heterostructures typically contain a high density of dislocations oriented parallel to the c-axis, of order 10^8 to 10^9 cm-2. It is of considerable importance to understand the effects of these large dislocation densities on electrical properties of GaN materials and devices. We have analyzed the strain and associated charge and potential in the vicinity of threading dislocations. We find that the strain associated with edge (and mixed) dislocations gives rise to a surface charge via the piezoelectric effect. In turn, this charge can induce a surface potential variation of a surprisingly large magnitude, of order 0.1 V for a single dislocation. Our analysis suggests that certain surface potential variations on GaN reported by Hansen et al.1 can be explained through this piezoelectric mechanism. Our analysis also leads to a simple procedure to identify the burgers' vectors of the dislocations. In a recent paper,2 we calculated the piezoelectric polarization and its associated charge density for threading dislocations oriented parallel to the c-axis in wurtzite GaN. It was shown that the polarization field generated by screw components of dislocations does not generate electric fields. Edge dislocations, however, produce polarization fields that have non-zero divergence at surfaces and interfaces, which induce a surface charge density with a dipole-like spatial distribution. In this work, we have used these earlier results to derive the potential variation on the surface due to these piezoelectric dipoles. The charges on the surface perturb the depth of depletion region, and hence cause a potential variation at the GaN surface. For a single edge dislocation, we calculate that a potential drop of 0.13V is induced near the dislocation (assuming the fermi level at the surface is unpinned). The induced 2-dimensional potential variation has its largest gradient at the dislocation position. The direction of the gradient is perpendicular to the edge component, be, of the Burgers vector. We have used these results to analyze experimental observations reported by Hansen et al.1, in which combined AFM (atomic force microscopy) and SCM (scanning capacitance microscopy) were used to produce images of surface morphology and the corresponding near-surface potential of MOCVD-grown GaN films on sapphire substrates. Surface potential variations of order 1V were observed. Our results suggest that certain spatial variations observed can be explained (in both magnitude and shape) through this piezoelectric mechanism. Surface potential variations of order 1V are expected to arise from the combined influence of several nearby dislocations. There may be, additionally, surface potential variations due to charges trapped at the dislocations (unrelated to the piezoelectric effects).3 P. J. Hansen, Y. E. Strausser, A. N. Erickson, E. J. Tarsa, P. Kozodoy, E. E. Brazel, J. P. Ibbetson, U. Mishra, V. Narayanamurti, S. P. DenBaars, and J. S. Speck, Appl. Phys. Lett. 72, 2247 (1998). C. Shi, P. M. Asbeck, and E. T. Yu, Appl. Phys. Lett. 74, 573(1999). 3 N. G. Weimann, L. F. Eastman, D. Doppalapudi, H. M. Ng, and T. D. Moustakas, J. Appl. Phys. 83. 3656 (1998) *This work has been partially funded by BMDO (Dr. Kepi Wu) and by ONR (Dr. John Zolper).

9:40 AM

Two Dimensional Electron Gas Density and Polarization Effects in AlGaInN/GaN Heterostructures: *J. W. Yang*[1]; Asif Khan[1]; R. Gaska[2]; G. Simin[1]; A. Bykhovski[2]; Michael S. Shur[2]; [1]University of South Carolina, ECE Dept., Columbia, SC 29208 USA; [2]Rensselaer Polytechic Institute, ECSE and CIEEM, Troy, NY 12180 USA

We report on the theoretical and experimental dependence of the two dimensional (2D) electron gas density in AlGaInN/GaN heterostructures on the composition and the thickness of the AlGaInN barrier thickness. Four different effects determine this dependence: (1) piezoelectric effects determined by strain, (2) by the difference of spontaneous polarization at heterointerfaces, (3) strain relaxation when the barrier thickness exceeds the critical thickness for the development of misfit dislocations, and (4) the barrier doping. The experimental data for the samples with the molar fraction of Al around 15% and In molar fraction up to 3 % show that the 2D electron gas density varies from $2 ? 3 \times 10^{12}$ cm-3 to 9×10^{12} cm-3 (with unintentional barrier doping). With the barrier doping up to approximately 5×10^{18} cm-3, the 2D-electron concentration increases to 1.8×10^{13} cm-3. Our calculations are based on the analytical self-consistent solution of the Poisson and Schrödinger equations at the heterointerface and on the calculations of the spontaneous and piezoelectric polarization as functions of the lattice mismatch based on the theory of elasticity. We also compare these results with similar data for AlGaN/GaN heterostructures with different Al molar fractions.

10:00 AM Break

10:20 AM +

Growth and Characterization of AlGaN/GaN Heterostructures: *Christopher J. Eiting*[1]; Damien J. H. Lambert[1]; Ho-Ki Kwon[1]; Bryan S. Shelton[1]; Mike M. Wong[1]; Ting-Gang Zhu[1]; Doris E. Lin[1]; Russell D. Dupuis[1]; [1]The University of Texas at Austin, PRC/MER-R9900, Microelectronics Research Center, Austin, TX 78712-1100 USA

We report the growth and characterization of high-quality AlGaN/GaN heterojunctions by low-pressure metalorganic chemical vapor deposition (MOCVD) in hydrogen with trimethylgallium (TMGa), trimethylaluminum (TMAl), silane (SiH_4), and ammonia (NH_3) precursors. We have varied the growth conditions (e.g., growth temperature, V/III ratio, growth pressure) and have studied the correlation of the symmetric and asymmetric X-ray diffraction linewidths, surface morphology, and modulation doping concentrations upon the mobility and sheet charge density of the two-dimensional electron gas (2DEG). AlGaN films with various alloy compositions have been used as the wide-bandgap layer in these structures. Some samples employed entirely undoped 2DEG structures while others contained modulation-doped heterostructures with various spacer layer thicknesses. We find that the 2DEG mobility is highly dependent on the growth conditions employed at the transition from GaN to AlGaN growth. Specifically, inserting a short NH_3/H_2 purge step just before AlGaN deposition results in improved mobility heterostructures relative to "continuous growth" or a "long purge". This purge presumably sweeps out leftover TMGa and promotes stoichiometric two-dimensional growth of AlGaN. Contrary to what is commonly reported for bulk GaN/sapphire epitaxial layers, preliminary 300K electrical data from these 2DEG films show no strong correlation between asymmetric (102) X-ray rocking curve FWHM values for the GaN layer and the electron mobility in the 2DEG. Such behavior might be expected if the electrons are confined to the two-dimensional layer at the AlGaN/GaN interface and thus the mobility is not strongly dependent on bulk properties. Surface atomic-force microscopy (AFM) measurements on 5x5 mm areas show RMS roughness values between 0.5 and 1.0 nm independent of the measured mobility. Electron sheet charge density in these heterostructures correlates well with mobility, higher sheet concentration s resulting in lower mobilities. By optimizing the growth conditions, we have achieved AlGaN(x=0.3)/GaN heterostructures on (0001) sapphire with 2DEG mobilities in excess of 1300 cm²/Vs at 300K and 4500 cm²/Vs at 100K with $n_s \sim 9.4 \times 10^{12}$ cm-2, corresponding to an $n_s m$ product of 1.2×10^{16} /Vs. The maximum $n_s m$ product was $1.53 \times 10 n_s m$ /Vs.

10:40 AM

Effect of Surface Roughness on Electron Mobility in AlGaInN/GaN Heterostructures.: *Asif Khan*[1]; Remis Gaska[2]; J. W. Yang[1]; Michael S. Shur[2]; [1]USC, ECE, Columbia, SC 29208 USA; [2]Rensselaer Polytechnic Institute, ECSE and CIEEM, Troy, NY 12180 USA

We report on the dependence of the electron Hall mobility and sheet two dimensional electron gas density on the thickness of the AlGaInN barrier layer in AlGaInN/GaN heterostructures. With the increase in the barrier thickness from 15 nm to 30 nm, the room-temperature electron Hall mobility increases only by 10% to 15%. However, at 80 K, the electron mobility increases from 6,000 cm2/V-s to approximately 10,300 cm2/V-s. We propose a model that links this increase to a new scattering mechanism related to the top surface roughness. This roughness leads to the variation of the electric potential in the 2D-electron channel caused by the piezoelectric and polarization effects. The effect is larger in for thinner barriers because of a larger relative change of the distance between the channel and the top surface. We present the results of the calculations of the electron mobility that accounts for this surface roughness. These calculations show that this 'piezo roughness' scattering is not strong enough in order to lead to an appreciable change of the electron mobility at room-temperature at which the polar optical scattering dominates. However, this effect is very important at cryogenic temperatures, in agreement with our experimental data. The results of the model are in agreement with our experimental data obtained by the Atomic Force Microscopy that show that the roughness of the top surface is on the order of 2 - 2.5 nm.

11:00 AM +

High Electron Mobility 2DEG in AlGaN/GaN Structures: *Chris R. Elsass*[1]; Yulia Smorchkova[2]; Erik Haus[1]; Paul Fini[1]; Pierre Petroff[3]; Steven P. DenBaars[3]; Umesh Mishra[2]; James Speck[1]; Ben Heying[1]; [1]University of California, Santa Barbara, Mats. Dept., Santa Barbara, CA 93106 USA; [2]University of California, Santa Barbara, ECE, Santa Barbara, CA 93106; [3]University of California, Santa Barbara, Mats. and ECE Dept., Santa Barbara, CA 93106

GaN and its alloys with AlN are considered to be promising materials for high power, high temperature electronic devices such as field-effect transistors and heterojunction bipolar transistors. There have been numerous reports on high quality AlGaN/GaN heterostructures grown by MOCVD with electron mobilities as high as 2050 cm2/Vs 9000 cm2/Vs (carrier density 1x1013 cm-2) at 300K and 77K, respectively (Gaska et. al., APL, 1999). Two-dimensional electron gas (2DEG) AlGaN/GaN structures have also been realized by molecular beam epitaxy (Li, et. al., J. Vac. Sci. Tech. B, 1998), however until recently their transport characteristics have been inferior to those grown by MOCVD. The best mobilities reported for MBE grown heterostructures are 1023 cm2/Vs at 300K and 4070 cm2/Vs at 77K (carrier density 1x1013 cm-2). UCSB MOCVD GaN (0001) n-type templates nucleated on sapphire were used for the MBE AlGaN/GaN growth. The 2-3 micron GaN template exhibited Hall mobility of 303 cm2/Vs and sheet carrier concentration of 2.5x1013 cm-2 at 300K. The nitride MBE growth reported here were grown in a Varian Gen II MBE system composed of two water-cooled EPI Unibulb Nitrogen Plasma sources utilizing ultrahigh purity nitrogen which was purified through an inert gas purifier (Aeronex, San Diego, CA) and convention Ga and Al effusion cells. Unintentionally doped MBE GaN was grown at 750°C on the template followed by AlGaN with a nominal thickness of 250 nm and 50 nm respectively. X-ray diffraction analysis reveal a nominal Al composition of 10%. Capacitance-Voltage measurements at 300K showed a sharp increase in the carrier concentration at the AlGaN/GaN interface. Temperature dependent Hall measurements showed a room-temperature mobility of 1150 cm2/Vs, 77K mobility of 14,500 cm2/Vs, increasing to 20,000cm2/Vs at 12K. The sheet carrier concentration varied from 1.4x1013 cm-2 at room-temperature to 4.8x1012 cm-2 at 12K. Because the sample was grown on n-type MOCVD GaN a parallel conduction path of low mobility carriers exist and significantly affects the room-temperature measurements. Using a two layer conduction model with one layer as the template and the second layer as the 2DEG, a room-temperature mobility of 1860 cm2/Vs with a carrier concentration of 4.8x1012 cm-2 was determined for the 2DEG. The magnetic field dependence of the longitudinal resistance of the AlGaN/GaN

heterostructure at 4.2K showed Shubnikov-de Haas oscillations starting at about 2.5 Tesla confirming the presence of a 2DEG at the AlGaN/GaN heterointerface. At a magnetic field of about 5 Tesla spin splitting of the Landau levels was observed which is indicative of a small amount of disorder at the AlGaN/GaN interface. Fourier analysis of the data yields a 2DEG sheet density of 5.2×10^{12} cm-2. The high quality of the 2DEG may be due to a number of factors. The AlGaN/GaN interface of the MBE films may have less roughness than corresponding MOCVD films. Zhang et. al.,(JAP 1999) have modeled AlGaN/GaN heterostructures and shown that the roughness of the interface is especially important in these films because of the proximity of the 2DEG to this interface. Fewer impurities in the MBE grown film compared to MOCVD grown films could also be the reason for increased mobility. This work was supported by ONR (C. Wood and J. Zolper contract monitors), AFOSR (G. Witt contract monitor) and NSF through the QUEST Center.

11:20 AM
Correlation Between Material Quality and Low-Frequency Noise Level in GaN Heterostructure Field Effect Transistors: *Alexander A. Balandin*[1]; Richard Li[1]; Shujun Cai[1]; Jiang Li[1]; Kang L. Wang[1]; E. N. Wang[2]; M. Wojtovicz[2]; [1]UCLA, Elect. Eng. Dept., Device Research Laboratory, Rm. 56-125B, Eng. IV Bldg., UCLA, Los Angeles, CA 90095 USA; [2]TRW Inc., Redondo Beach, CA 90278 USA

Advances in GaN-related compound materials and heterojunction field effect transistors (HFET) have led to demonstration of high power density microwave operation of these devices. GaN HFETs exhibiting the cutoff frequency of 60 GHz and the maximum frequency exceeding 100 GHz have been recently reported by this group [1]. We have also shown that GaN HFETs grown on sapphire can operate with low flicker noise levels which are required for the microwave applications, particularly low-phase noise amplifiers [2]. However, little is known about the physical origin of the low-frequency noise in GaN HFETs and the effect of the material quality on the noise level. The reported values of the Hooge parameter vary as much as 4 orders of magnitude. It is also not clear what model (the mobility fluctuation or the number fluctuation through random carrier trapping-detrapping) describes the 1/f noise in GaN systems the best. It has been previously shown that GaN/AlGaN heterostructures have large piezoelectric coefficients which lead to strong electric polarization on (0001) faces of the wurtzite structures typically used to form GaN HFETs. The latter results in appreciable charge densities which are large enough to design HFETs without any channel doping. Due to this reason it is particularly interesting to know how the channel doping influences the low-frequency noise in GaN devices. In this presentation we report detailed low-frequency noise measurements in a doped and an undoped channel GaN/AlGaN HFETs grown on semi-insulating 4H-SiC substrates. A higher aluminum content of the undoped channel devices leads to a higher piezoelectrically induced charge density, thus making up for the absence of doping and allowing for a meaningful comparison of the noise levels for both types of the devices. Our results reveal a two-orders-of-magnitude reduction in the input-referred noise spectral density of the undoped channel device with respect to the noise density of the doped channel devices with comparable electric characteristics. The low-temperature noise spectra for doped devices show clear g-r-type peaks in the saturation region of operation. In order to clarify the effect of the material quality on the noise characteristics, we have conducted DLTS studies of GaN devices. The activation energies for the doped channel GaN HFETs grown on SiC were found to be in the range from E=0.20 eV to E=0.37 eV. The activation energy for doped channel GaN HFETs grown on sapphire had a higher value of E=0.85 eV. The DLTS data were compared with the corresponding low-frequency noise characteristics of these devices. The Hooge parameter extracted for GaN devices was comparable to that one of commercial GaAs devices and strongly depended on the doping concentrations and material quality. The authors gratefully acknowledge the support of DoD MURI-ARO program on Low Noise Electronics. [1]. S.J. Cai, R. Li, Y.L. Chen, L. Wong, W.G. Wu, S.G. Thomas, and K.L. Wang, Electron. Lett., 34, 2354 (1998). [2]. A. Balandin, S. Cai, R. Li, K.L. Wang, V. Ramgopal Rao, and C.R. Viswanathan, IEEE Electron Device Lett., 19, 475 (1998).

11:40 AM
Characterization of GaN MIS Structures: *Tamotsu Hashizume*[1]; Ryuusuke Nakasaki[1]; Hideki Hasegawa[1]; [1]Hokkaido University, Research Center for Interface Quantum Electr. (RCIQE) and Graduate School of Electr. and Info. Eng., Kita-ku, Kita 13 Nishi 8, Sapporo, Hokkaido 060-8628 Japan

GaN-based field-effect transistors (FETs) or heterostructure FETs utilizing Schottky barrier gate have been fabricated and their potential use for the high-power electronics devices has been demonstrated. However, formation of Schottky contacts stable at high temperatures has not been achieved yet. In contrast to Schottky gate structures, metal-insulator-semiconductor (MIS) structures have the advantage of utilizing chemically stable insulators at the interface, which is very attractive for the application to high-power and high-temperature devices. In fact, Kawai and co-workers [1] have very recently demonstrated good d.c. performance of the insulated-gate heterostructure FET using a AlN/GaN MIS structure. However, very little is known about interface properties of GaN MIS systems. In this paper, interface properties of GaN MIS structures were systematically characterized by current-voltage (I-V), capacitance-voltage (C-V), x-ray photoelectron spectroscopy (XPS) and Raman spectroscopy methods. Si-doped GaN layers ($n=1-3\times10^{17}$ cm-3) grown on sapphire substrates by metal organic chemical vapor deposition (MOCVD) were used. SiO_2/n-GaN and Si_3N_4/n-GaN structures were prepared by rf-plasma CVD using N_2O and SiH_4, and by electron cyclotron resonance (ECR) plasma CVD using N_2 and SiH_4, respectively. Just prior to the deposition of insulating films, some GaN surfaces were treated in NH_4OH-based solution at 50°C for 15 min and in N_2 plasma for 1 min. Al was used for both of ohmic and gate contacts. Poor C-V characteristics were observed for the SiO_2/GaN structures without surface treatments. Very limited variation of capacitance (near flat C-V curve) reflected the existence of high density of interface states in the range of 10^{13} cm-2eV-1. Treatment of GaN surfaces in NH_4OH-based solution was found to enhance the capacitance change in C-V characteristics. Further improvement was obtained by an additional N_2 plasma treatment in PECVD chamber just prior to the SiO_2 deposition. Relatively low value of interface state density, D_{it}, of 2-3 x 10^{11} cm-2 eV-1, was obtained around the energy position of Ec-0.5eV in the samples with NH_4OH-solution and N_2-plasma treatments. This seems to be related to the removal of native oxides on GaN surfaces during the NH_4OH treatment and the formation of slightly N-rich GaN surfaces by subsequent N_2-plasma treatment, as confirmed by an XPS analysis. Furthermore, ECR-CVD prepared Si_3N_4/n-GaN structures with NH_4OH-solution and N_2-plasma treatments showed even better C-V characteristics. Clear deep depletion behavior was observed at room-temperature, similar to that of wide-gap semiconductor MIS structures such as SiO_2/SiC. Thus, the surface potential of GaN could be controlled over a remarkably wide potential range by the gate voltage. A minimum D_{it} value of 1x 10^{11} cm-2 eV-1 or less was realized around the energy position of Ec-0.8eV in the Si_3N_4/n-GaN structures. [1] H. Kawai, M. Hara, F. Nakamura, and S. Imanaga, Electron. Lett., 34, 592(1998).

Session M. SiC Growth & Characterization

Thursday AM   Room: Multicultural Center Theater
July 1, 1999   Location: University Center

Session Chairs: Marea Skowronsici, Carnegie Mellon University, Pittsburgh, PA USA; Shigehiro Nishino, Kyoto Institute of Technology, Kyoto, Japan

8:20 AM +

Formation of Macrodefects in SiC Physical Vapor Transport Growth: *Edward Kyle Sanchez*[1]; Volker D. Heydemann[2]; Tom Kuhr[1]; Gregory S. Rohrer[1]; Marek Skowronski[1]; [1]Carnegie Mellon University, Mats. Sci. and Eng., 5000 Forbes Ave., 138 Roberts Hall, Pittsburgh, PA 15213 USA; [2]II-VI Inc., 375 Saxonburg Blvd., Saxonburg, PA 16056 USA

It is well known that filamentary voids propagating along the c axis of SiC single crystals form during physical vapor transport (PVT) growth. Most publications interpret all of them as being empty core superscrew dislocations. We present evidence that they are actually two separate classes of filamentary voids that have distinct natures and origins. We propose the term "micropipes" should be reserved for cylindrical voids with diameters in the range of 0.1 to 5.0 mm, that form at the core of a superscrew dislocation and are aligned parallel to the [0001] axis. The second type of filamentary void, macrodefects, have diameters from 10 to 100 mm and are not associated with dislocations. They have been observed to be associated with carbon inclusions and they always start at the interface between the SiC seed and the graphite crucible lid. We believe that they are formed by localized decomposition of the seed crystal. To indicate how high this rate of backside decomposition can be, a seed was mechanically mounted with an intentional gap of approximately 100 mm between the seed and graphite lid. This high rate of transport resulted in the entire seed evaporating and redepositing as polycrystalline material. We also show that macrodefects are associated with the non-uniformity of the seed attachment. The typical mounting procedure involves the mounting of the seed to the crucible lid by "gluing" it with graphitized sugar. The resulting layer is inherently inhomogeous. The non-uniformity of this bond on the backside leads to preferential evaporation of the seed and the resulting tubular macrodefects. Several possible approaches of preventing macrodefects were investigated. The main focus was on the deposition of a thin, continuous diffusion barrier layer on the backside of the seed, which would be stable at the growth temperature of 2300°C. Two different layers were used, a sputtered layer of Ta of about 1mm and a layer of graphite. The graphite layer was formed by spinning photoresist onto the backside and annealing this layer at 1200°C. Upon heating the Ta-protected seed to 2300°C the layer was changed to TaC. This layer protected the seed at the initial stages of growth, however after long growth runs the layer did not stay uniform and resulted in the formation of macrodefects. The graphite layer appeared to remain stable at the growth temperature of 2300°C. This stability resulted in the elimination of macrodefects in small area seeds. We suggest that the presence of a stable diffusion barrier on the backside of SiC seeds will prevent the formation of macrodefects in PVT growth.

8:40 AM

Local Epitaxy and Epitaxial Lateral Overgrowth of SiC: *Igor Ivanovich Khlebnikov*[1]; Yuri Igorevich Khlebnikov[1]; J. A. Freitas[2]; Tangali S. Sudarshan[1]; [1]University of South Carolina, Dept. of Elect. & Comp. Eng., 301 S. Main St., Columbia, SC 29208 USA; [2]Naval Research Laboratory, Electr. Sci. and Tech. Div., 4555 Overlook Ave., S.W., Washington, DC 20375-5347 USA

The selective area epitaxial growth of SiC within a graphite mask window is an important technology for fabricating various kinds of devices based on this material. In this paper we report for the first time the growth of a low dislocation density layer on a SiC substrate using the epitaxial layer overgrowth technique. The selective area SiC growth reported here is accomplished using the physical vapor transport (PVT) epitaxy. The growth was carried out on 6H-SiC wafers with on- and 8° off-oriented from the basal plane in the <1120> direction. A graphite mask, consisting of rows and columns of uniformly spaced open squares (50x50mm) was used for the selective nucleation of the silicon carbide mesa structures. Hexagonal shaped structures were successfully grown by using selective area PVT epitaxy. Essentially, there is no direct deposition of the SiC on the graphite film. A lateral/vertical growth rate ratio of 6 was achieved. The optical and scanning electron microscope images show perfectly formed hexagonal islands, which are located over the open square windows. High lateral resolution Raman spectroscopy (probe size 1mm) has been used to investigate the structural (polytype, crystal order) and electronic (carrier concentration) properties of these structures. Changes in the Raman parameters across the lateral mesa structure are reported. The results suggest that the selective area epitaxial growth of SiC is a promising technique for obtaining a high quality of the locally grown structures for SiC device applications.

9:00 AM

Susceptor Effects on 4H-SiC Epitaxial Growth: *Barbara E. Landini*[1]; [1]ATMI, 7 Commerce Dr., Danbury, CT 06810 USA

Susceptors typically used in SiC vapor phase epitaxial processes are vulnerable to etching and degradation in the high temperature hydrogen growth ambient. Susceptor deterioration can give rise to undesirable changes in the epilayer morphology and impurity incorporation. To help identify an optimal susceptor material, the impact of different susceptor materials on 4H-SiC epilayer growth was investigated. The morphologies, intentional doping properties, and unintentional impurity incorporations of epilayers up to 11 microns thick were compared for films grown using the different susceptors. Four different susceptor materials were compared for the growth of 4H-SiC epilayers using vapor phase epitaxy. The use of graphite susceptors with a carbon-based coating resulted in 4H-SiC epilayers with smooth morphologies, as measured using Nomarksi and AFM, and uniform intentional nitrogen doping profiles as measured by SIMS analysis. However, the unintentional aluminum concentration in the epilayers measured using SIMS analysis was very high when these susceptors were used, and the susceptor lifetime was short. The use of SiC-coated graphite susceptors resulted in the transfer of a polycrystalline SiC layer from the susceptor to the wafer backside. Although the unintentional impurity concentrations were low, epilayers grown using SiC-coated susceptors tended to display degraded morphologies and more non-uniform nitrogen doping profiles compared to epilayers grown using identical growth parameters on other susceptors. Two different metal carbide coatings were investigated. The growth rates of films grown using the two metal carbide coated susceptors were comparable to each other and to the carbon-coated susceptors for identical growth parameters. Nomarksi and AFM analysis confirmed smooth morphologies for epilayers up to 11 microns thick. No thick backside polycrystalline SiC deposit was observed. The unintentional epilayer aluminum concentration measured by SIMS analysis was reduced by more than an order of magnitude compared to the carbon-coated susceptors. The intentional doping could be controlled over several orders of magnitude via site competition epitaxy or nitrogen partial pressure variation. Aluminum doping was demonstrated using metal carbide coated susceptors, and abrupt p-n junctions were achieved. The lifetime of metal carbide coated susceptors was several times longer than the lifetime of the carbon-coated susceptors.

9:20 AM

Epitaxial Growth of 6H-SiC on Spherically Polished 6H-SiC Substrate Using Si_2Cl_6+C_3H_8 +H_2 by CVD: *Shigehiro Nishino*[1]; Yasuichi Masuda[1]; Yuki Nishio[1]; [1]Kyoto Institute of Technology, Dept. of Electr. and Inform. Sci., Faculty of Eng. and Design, Matsugasaki, Sakyo-ku, Kyoto 606 Japan

It is important to know the morphology dependence of the orientation of the the substrate. Most of the homoepitaxial growth is carried out on the tilted (0001) basal plane toward <11-20> direction. In this presentation,we show the properties of 6H-SiC epilayer grown on a spherically polished 6H-SiC(0001) substrate. The substrate was made from bulk SiC prepared by sublimation method. Tilted angle varied 0 to 9 degree-off from the (0001) basal plane. Crystal growth was carried out at a substrate temperatute of 1500°C using $Si_2Cl_6+C_3H_8+H_2$ by atmospheric CVD. The CVD system in this study was made from a horizontal quartz-tube with water cooling jacket. The spherically polished substrate was placed on SiC coated graphite susceptor. Typical growth condition was as follows: flow rate of Si_2Cl_6=0.45 sccm, C/S=10, H_2=3 slm, substrate temperature(Ts)=1500°C, growth period=5 h. The growth rate=3 um/h. The growth rate was mainly limited by flow rate of Si_2Cl_6 and independent of flow rate of C_3H_8. Six fold star-like symmetric pattern was observed by naked eye on the substrate. Very rough surface appeared along <1-100> direction, however, rather smooth surface appeared along <11-20> direction. Color of the photoluminescnece from the epilayer on the substrate measured by dipping the sample in the liquid nitrogen also showed six fold symmetry. Overall distribution of the polytypes was determined using color mapping by camera. 3C-SiC grew along the <1-100> direction and 6H-SiC grew along the <11-20> direction. Smooth surface was obtained near the off-angle at around 9 degree along <11-20> direction. Polytype of star-like pattern of the epilayer was deteremined by PL spectra measurement. Surface morphologies were different between 6H-SiC epilayers and 4H-SiC epilayers, and depended strongly on C/Si ratio and Si flow rate. Defects density was dependent on etching step, indicating that pre-growth etching is very important and effective. As a result of growth rate measurement, activation energy was 7.90 kcal/mol. Homoepitaxial relationship between epilayer and the substrate was confirmed by measurements of Raman and PL spectroscopies. Donor concentration of epilayer was about 5X10^{15} cm^{-3} and electron mobility was 283 cm[2]/Vs at room-temperature. A Schottky diode with a breakdown voltage of -490 V was fabricated. PN diodes were prepared and green emission of light was observed and the light could be related to Ti impurity.

9:40 AM +
Crystalline Quality and Polytype Formation of SiC Films Grown With Different Concentrations of Ge on (111) Si Substrates: *Wendy L. Sarney*[1]; Lourdes G. Salamanca-Riba[1]; P. Zhou[2]; Crawford Taylor[2]; Michael Spencer[2]; R. P. Sharma[1]; K. A. Jones[3]; [1]University of Maryland, College Park, Dept. Mats. & Nuclear Eng., Bldg. 090, College Park, MD 20742 USA; [2]Howard University, Mats. Sci. Center of Excellence, 2300 6th St. NW, Washington, DC 20059 USA; [3]U.S. Army Research Lab, Adelphi, MD 20783 USA

SiC films grown on Si usually exhibit poor crystalline quality and contain a high density of stacking faults. Typically, high growth temperatures of approximately 1450°C are needed to obtain high quality SiC films. Adding Ge should limit adatom diffusion and allow us to grow at 1000°C without the usual negative low temperature growth characteristics of surface roughening or poor crystalline quality. We added Ge in the form of GeH_2 to the reactant gases during the growth of SiC films on (111) Si substrates at 1000°C to promote two-dimensional growth and inhibit stacking fault formation. TEM results show that the crystalline quality and interface sharpness significantly improve with increasing Ge concentration. SiC films grown with only a trace amount of Ge were primarily amorphous. High resolution lattice images and corresponding diffraction patterns indicate the films grown with 10 sccm Ge are polycrystalline and have the 3C polytype. The TEM lattice image of the sample grown with 15 sc cm Ge showed slightly improved crystallinity, but otherwise was not appreciably different from the sample with 10 sccm. The sample grown with 20 sccm Ge contains both the 3C and 6H polytypes of SiC. The presence of the hexagonal structure is evident by the zig-zag stacking sequence seen in the high resolution image and the presence of the hexagonal spots in the diffraction pattern. The initial structure formed on the substrate is 3C SiC, which ends abruptly and is followed by 6H SiC. While stacking faults are present near the film's surface in the 6H region and near the substrate/film interface in the 3C region, the majority of the 6H region is single crystalline and of high structural quality. We will discuss the growth

procedures and the effect different concentrations of Ge has on film polytype and quality.

10:00 AM Break

10:20 AM
Deep Donor in Bulk n-type 4H-SiC: *W. C. Mitchel*[1]; A. Saxler[1]; Ronald E. Perrin[1]; John Sizelove[1]; S. R. Smith[1]; J. S. Solomon[1]; A. O. Evwaraye[2]; [1]Air Force Research Laboratory, Mats. and Manuf. Div., AFRL/MLP, Wright-Patterson AFB, OH 45433-7707 USA; [2]University of Dayton, Dept. of Phys., 3000 College Park, Dayton, OH 45469 USA

Bulk n-type 4H-SiC wafers have been studied with temperature dependent Hall effect, deep level transient spectroscopy (DLTS) and secondary ion mass spectroscopy (DLTS). Hall effect data was taken up to 1000K and the carrier concentration versus inverse temperature data was fitted to the multi-center charge balance equation. In addition to the two levels due to nitrogen near 50 and 100 meV, we observed a deeper level between 0.3 and 0.5 eV. The level is seen as an additional slope in the n vs 1000/T curves at the highest temperatures after the nitrogen levels start to saturate. This level was seen in several samples from two different suppliers. Hall effect fitting gives concentrations between 5X10^{16} to 5X10^{17} cm^{-3} for the level in different samples with energies between 0.3 and 0.5 eV. This level has only been seen by Hall effect in material with moderate to low nitrogen concentrations, below 1018 cm-3 in all cases and usually in the low 10[p/17] cm^{-3} range. SIMS studies of the purest sample in which this level was seen, at a concentration of 5X10^{16} cm^{-3}, did not detect any impurities at that concentration. We do not know of any reported impurity related donor level in this energy range that this can be associated with this defect. Oxygen, which was not searched for in the SIMS experiments, could be present in the material. Intrinsic defects are usually not present in as-grown SiC at these concentrations. DLTS experiments on these samples will be reported as well.

10:40 AM +
Radiotracer Spectroscopy on Ta Related Deep Levels in 4H-SiC: *Joachim Kurt Grillenberger*[1]; Norbert Achtziger[1]; Rainer Sielemann[2]; [1]University of Jena, Institut für Festkörperphysik, Max-Wien-Platz 1, Jena 07743 Germany; [2]Hahn-Meitner-Institut, FD, Glienicker Straße 100, Berlin 14109 Germany

Recent publications on growth of Silicon Carbide bulk crystals report on tantalum crucibles acting as growth containment [1]. Thus, Ta represents a possible contamination in these SiC crystals and its influence on the electrical properties of SiC is of high technological relevance. The present study was directed to the investigation of Ta-related deep levels in the band gap of n-type 4H-SiC by means of Deep Level Transient Spectroscopy (DLTS). Though this technique is very sensitive to the concentration of a trap, it does not reveal its chemical or structural nature. Applying this technique to radioactive isotopes instead of stable impurity atoms, a definite chemical identification of related energy levels in the band gap can be deduced by the well-known half-life of the nuclear decay[2]. The samples were n-type 4H-SiC epitaxial layers grown by Cree Research Corporation with a net donor concentration of 5´1015 cm-3. The radioactive impurity 177Ta (decay to 177Hf, half life 56.6d) was recoil implanted using nuclear reactions of 16O ions on a 165Ho target foil. Implantation damage was annealed at 1600 K (4h, O2) or 1900 K (5min., Ar) + 1600 K (30min., O2) in sealed quartz ampoules. In the DLTS-spectra only one small peak of variable height was found. It is, however, superimposed by strong background-peaks preventing the standard DLTS data-analysis. Taking into account the fact that DLTS-spectra are highly reproducible for constant trap concentrations, the initial measurement was subtracted from the spectra measured later during the nuclear decay of Ta. Hence, only Ta-related peaks remain, and their exact peak position could be determined precisely. The extracted spectra exhibit a broad peak at about 290 K. The width indicates possibly a splitting of this level with a mean energy at 0.62 (3) eV below the conduction band (capture cross section s =3.0´1016 cm2). To further confirm the results of this radiotracer experiment, stable 181Ta isotopes were implanted in n-type 4H-SiC samples. To achieve a fairly homogeneous Ta concentration of about 2´1014cm-3, a six-fold Ta-implantation was per-

formed with implantation energies between 1.0 and 6.2 MeV. The DLTS-spectra of these 181Ta implanted samples also reveal the Ta-related trap; additional peaks were assigned to defect-related traps created during the ion implantation.

11:00 AM

Effect of NO Annealing Conditions on Electrical Characterization of n-type 4H-SiC MOS Capacitors: *Hui-feng Li*[1]; Denis Sweatman[1]; Sima Dimitrijev[1]; H. Barry Harrison[1]; [1]Griffith University, School of Microelectronic Eng., School of Microelectronic Eng., Griffith University, Brisbane, QLD 4111 Australia

Silicon carbide is a promising wide bandgap semiconductor material for high temperature and high power devices applications. A distinct advantage of SiC is that it can be thermally oxidized in a similar way to Si. However, the quality of thermal oxides on SiC is inferior to that on Si. XPS analysis reveals a complex SiO_2-SiC interface with appearance of silicon oxycarbide compounds at the interface. We have suggested NO nitridation as a method of improving the SiO_2-SiC interface. It has been shown by XPS analysis that NO nitridation removes the silicon oxycarbide compounds from the interface and produces more ordered interface. Reduced interface trap densities are measured in NO annealed SiC MOS capacitors. This paper presents the first results of the effect of NO annealing temperature and NO annealing time on the electrical properties of n-type 4H-SiC MOS capacitors. The n-type 4H-SiC MOS capacitors are annealed in NO at temperatures from 930°C to 1130°C. The interface trap densities measured by conductance technique at 330°C decrease as NO annealing temperature increases from 930°C to 1130°C, minimum interface trap density being 1.1×10^{11} eV^{-1} cm^{-2} for samples annealed at 930°C and 2.1×10^{10} eV^{-1} cm^{-2} at 1130°C. However, the net oxide charge of all samples is negative calculated from room-temperature flatband voltage. The net oxide charge is a results of compensation between different types of charges in the oxide and at the interface. C-V curves measured at 300°C show negative flatband voltage shifts, indicating the appearance of positive charge at high temperature. The changes in net oxide charge between room-temperature and 300°C are calculated and used to compare different samples [1]. The change in net oxide charge decreases as NO annealing temperature increases from 930°C to 1130°C, which is consistent with the dependence of interface trap density measured by conductance technique on NO annealing temperature. The interface trap densities and the changes in net oxide charge between room-temperature and 300°C also decrease as NO annealing time increases from 30 minutes to 180 minutes. However, extended NO annealing at a certain temperature does not help reduce interface trap density significantly. In summary, NO annealing temperature has more pronounced influence on the SiO_2-SiC interface than the annealing time. [1] D. M. Brown and P. V. Dray, J. Electrochem. Soc., Solid State Sci., Vol. 115, No.7, pp.760-766 (1968)

11:20 AM   Late News

11:40 AM   Late News

Session N. Infrared Materials and Devices

Thursday AM   Room: State Street
July 1, 1999   Location: University Center

Session Chairs: Robert M. Biefeld, Sandia National Laboratory, Dept. 1113, Albuquerque, NM USA; Tom Boggess, University of Iowa, Iowa City, IA USA

8:20 AM

Influence of Interfacial Layers on GaAsSb/InP Heterostructures: Xiangang Xu[1]; Jinsheng Hu[1]; Nouredine Matine[1]; *Simon P. Watkins*[1]; Colombo R. Bolognesi[1]; [1]Simon Fraser University, Dept. of Phys., 8888 University Dr., Burnaby, BC V5A 1S6 Canada

We report the growth of InP/GaAsSb/InP heterostructures lattice-matched to InP substrates in the temperature range 540-590°C. The surface morphology is found to be very sensitive to the exact interface growth procedure. Direct growth of GaAsSb on InP was found to yield very poor morphology, however, insertion a thin interface layer of InGaAs results in excellent surface quality. The role of the InGaAs layer on the type II low temperature photoluminescence at the interface will be briefly discussed. We found that Sb has a strong memory effect in our horizontal reactor system. Surprisingly Sb has a much higher incorporation efficiency than P in InPSb at these growth temperatures, which enhances the memory effect. The effect of variations in the growth conditions on the performance of double heterojunction bipolar transistors will also be briefly discussed.

8:40 AM

MOCVD Growth of InAsSb/InPSb SLS's for Use in Infrared Emitters: *Robert M. Biefeld*[1]; Steven R. Kurtz[1]; Jamie D. Phillips[1]; [1]Sandia National Laboratory, 1113, MS 0601, P.O. Box 5800, Albuquerque, NM 87185-0601 USA

We are continuing to explore the growth by metal-organic chemical vapor deposition (MOCVD) of novel mid-infrared (3-5 μm) infrared emitters (lasers and LED's) for use in infrared emitters and chemical sensor systems. As-rich, InAsSb heterostructures display unique electronic properties that are beneficial to the performance of these midwave infrared emitters. Previously we have made gain-guided, injection lasers using not intentionally doped, p-type AlAs0.16Sb0.84 for optical confinement and both strained InAsSb/InAs MQW and InAsSb/InAsP strained-layer superlattice (SLS) active regions. We have also reported the first ten-stage cascaded lasers and LED's with type I InAsSb/InAsP quantum-well active regions grown by MOCVD. These cascaded lasers employ a (p) GaAsSb/ (n) InAs semimetal electron/hole source between stages. In compressively strained InAsSb SLSs, it is necessary to maximize the light-heavy ($|3/2,\pm 1/2>$ - $|3/2,\pm 3/2>$) hole splitting to suppress non-radiative Auger recombination. We are currently exploring the growth of new emitter structures as well as the use of novel materials in these structures in an attempt to further reduce the Auger recombination by increasing the hole confinement using InPSb. We will describe the MOCVD growth of novel emitter active regions as well as the growth of InP1-xSbx layers, and InAsSb/InPSb SLS active regions for use in mid-infrared emitters. These materials were grown in a high speed rotating disk reactor. By changing the layer thickness and composition of InAsSb/InPSb SLSs, we have prepared structures with low temperature (<20K) photoluminescence wavelengths ranging from 3.4 to 4.8 μm. Initial quantum confinement data indicate that there is about a factor of two greater in the valence band offset between InPSb and InAsSb than for InAsP and InAsSb. Results for devices fabricated from these new structures and materials will be presented as they become available. *This work was supported by the US DOE under Contract No. DE-AC04-94AL85000. Sandia is a multiprogram laboratory oper-

9:00 AM +

MBE Growth of High Quality InGaAsSb/AlGaAsSb Heterostructures Using the Digital Alloying Technique: *C. Mourad*[1]; K. J. Malloy[1]; R. Kaspi[2]; [1]Center for High Technology Materials, University of New Mexico, Albuquerque 87106 NM; [2]Air Force Research Laboratory, AFRL/DELS, Kirtland, AFB 87117

Growth of high quality mixed anion alloys such as InGaAsSb and AlGaAsSb are critical to laser heterostructures designed for 2-4 micron emission. However, run-to-run reproducibility as well as the ability to reproducibly change alloy compositions within a heterostructure tend to be poor. This is because the competition for incorporation between the two anions (As and Sb) is extremely sensitive to a large number of growth parameters such as temperature, incident fluxes, and growth rate, which may drift during the course of deposition, or are difficult to reset during growth. With the intent of improving reproducibility, we have grown and characterized InGaAsSb and AlGaAsSb "digital alloys" deposited using modulated incident As2 and Sb2 incident fluxes. For example, $In_{0.1}Ga_{0.9}As_ySb_{1-y}$ alloy layers were grown by alternately exposing the film surface to As_2 and Sb_2 fluxes with a periodicity ranging from ~9 to ~22 Angstroms. Average alloy composition is determined by the duty-cycle of the anion-oven shutters. Structural characterization using high-resolution x-ray diffraction (XRD) shows clear satellite peaks indicating that the digital alloys retain the composition modulation. Optical characterization using photoluminescence indicate that the digital alloys can successfully replace the conventionally grown quaternary alloys with the same average composition. Guidelines in selecting periodicity and growth temperature will be presented. Digital growth of InGaAsSb and AlGaAsSb layers has enabled the growth of heterostructures containing multiple alloy compositions by toggling between shutter duty-cycles during growth, without necessitating changes to the oven temperatures throughout deposition. This minimizes a large source of error in reproducibility. In addition we have characterized digitally grown InGaAsSb layers using XRD and measured the sensitivity of the resulting average composition to the growth temperature. We find that the composition of $In_{0.1}Ga_{0.9}As_ySb_{1-y}$ alloy layers grown digitally on GaSb substrates is nearly three times less sensitive to the growth temperature as conventional growth. We have grown and characterized optically pumped ~2μm laser structures with InGaAsSb quantum wells and AlGaAsSb barriers both grown using the digital alloy technique. Room-temperature operation, a low threshold current density of 104 W/cm^{2} (at 80K with 808nm pump), and a large characteristic temperature (T_o) of 240 K show the feasibility of applying digital alloying techniques to mid-infrared optical devices.

9:20 AM

InSb Based Mid-IR Light Emitting Diodes and Lasers: *Tim Ashley*[1]; David T. Dutton[1]; C. Tom Elliott[1]; Neil T. Gordon[1]; Andrew D. Johnson[1]; Tim J. Phillips[1]; Graham J. Pryce[1]; Graham Berry[2]; Ben N. Murdin[3]; Eoin P. O'Reilly[3]; [1]Defence Evaluation & Research Agency, St. Andrews Rd., Malvern, Worcestershire WR14 3PS UK; [2]University of Wales, Cardiff, Dept. of Physics & Astronomy, P.O. Box 913, Cardiff, Wales CF2 3YB UK; [3]University of Surrey, Dept. of Phys., Guildford, Surrey GU2 5XH UK

Infrared photon sources have many potential advantages over thermal sources in terms of spectral output, speed of response and efficiency. Sources based on various III-V and II-VI materials have been reported recently. We describe InSb based light emitting diodes, both positive and negative luminescent, and diode lasers operating at midinfrared wavelengths. The devices are grown by molecular beam epitaxy and are, generically, in the form of a pseudo-double heterostructure. The LEDs have an active region which is up to 4microns thick and comprises InSb, InGaSb or InAlSb to give wavelength control over the mid-IR part of the spectrum. The devices are intended for applications requiring relatively large areas, of the order centimetres square, such as uniformity correction in thermal imagers and IR radiation shielding, therefore total Dr. current is an issue. A problem common to all LED structures is the low value for optical efficiency, of approximately 5%, caused by the high refractive index of the semiconductor leading to a large degree of internal reflection. We describe optical efficiency im-

provements which are achieved by implementing the concept of nonimaging concentrators. The active layer of the device is arranged at the narrow end of a cone, which is formed by a dry etching process which alternately removes the semiconductor or the resist, with emission from the wide end. The active device area is a small proportion of the emission area, so reducing the Dr. current, and reflections from the sides of the concentrator ensure that most generated light reaches the emission surface within the critical angle. Thus high external efficiency devices can be made. Results from devices with emission area of up to 3cm^2 will be described. In the case of lasers, at the very high injection levels required for stimulated emission, Auger recombination and intervalence band absorption become major loss mechanisms which prevent high output powers and/or high operating temperatures. We examine the use of strained superlattice structures comprising various numbers of InSb wells and InAlSb or InGaSb barriers to reduce the Auger recombination rate and intervalence band absorption coefficient in mid-IR lasers. Experimental results are presented which compare lasers which have either bulk or superlattice active regions. At 3.8microns wavelength, the maximum operating temperature which has been achieved under pulsed operation is 165K and the maximum CW power at 80K is 6mW.

9:40 AM

New Techniques for Epi-Down Mounting of Mid-IR Type-II Quantum-Well Lasers: *Edward Hugh Aifer*[1]; William W. Bewley[1]; Christopher L. Felix[1]; Linda J. Olafsen[1]; Igor Vurgaftman[1]; Donna W. Stokes[1]; Jerry R. Meyer[1]; [1]Naval Research Laboratory, Optical Sciences, Code 5613, 4555 Overlook Ave., Washington, DC 20375 USA

The development of improved type-II InAs/GaSb based quantumwell diode and cascade lasers for high power cw operation in the mid-IR, depends not only on electronic design considerations, but also on device packaging issues if optimal performance is to be obtained. Epi-side down mounting is essential for devices with dissipation levels of several watts, but it also introduces problems associated with having optical cladding and active regions in close proximity to the heat sink. Recently we have reported excellent heat sinking for optically pumped structures mounted epi-side down directly onto diamond heat-spreaders using mechanical force. Electrically-pumped devices present a more complicated challenge. Outside the contact stripe, passivation and insulation are required for isolation trenches that can be several microns deep. Because process temperatures much above 300°C are prohibited in this material system, low temperature CVD oxides or nitrides must be used. These tend to be thin, have poor sidewall coverage, and exhibit pinholes particularly over large areas. Furthermore, the devices are highly non-planar, with exposed trenches providing voids for solder, as well as precluding solderless pressure mounting techniques. Recent trends in interconnect technology developed by IBM for multilevel integrated circuits however, may remedy this situation. The new techniques are based on thick films of polyimide dielectric, which has excellent trenchfilling and smoothing characteristics, in conjunction with electroplated copper metallization. Devices are then globally planarized by chemical-mechanical polishing. In this presentation we discuss our procedures and the results of introducing these techniques to mid-IR laser applications.

10:00 AM Break

10:20 AM

Linewidth Enhancement Factor in Mid-Infrared Semiconductor Laser Active Regions: *Michael E. Flatte'*[1]; J. T. Olesberg[1]; Thomas F. Boggess[1]; [1]The University of Iowa, Dept. of Phys. and Astronomy, 100 IATL, Iowa City, IA 52242 USA

The linewidth enhancement factor is a fundamental parameter that characterizes the limit of spectral purity and the tendency for filamentation in a semiconductor laser. For either narrow-line or highpower operation, it is generally desirable that the linewidth enhancement factor be minimized. This parameter depends primarily on the magnitude and shape of the differential gain spectrum of the active region material. In mid-infrared laser materials, band structure engineering has been used routinely to minimize the effects of nonradiative recombination. This same approach can be used to tailor the differential gain spectrum of these materials to minimize the linewidth en-

hancement factor. It has been shown that the linewidth enhancement factor goes to zero near the peak of the differential gain. Unfortunately, in interband lasers, the peak of the differential gain is shifted away from the peak of the gain spectrum due to the imbalance between the valence and conduction band densities of states. The primary strategies for reducing the linewidth enhancement factor in semiconductor lasers have been 1) to p-dope the active region to partially offset the density of states imbalance, and 2) to use a DFB to detune the lasing frequency toward the peak of the differential gain. The situation is more challenging for mid-infrared semiconductor lasers since the conduction band effective mass of a bulk material decreases roughly proportionally with the band gap, which increases the density of states mismatch. In addition, p-doping the active region aggravates existing problems with Auger recombination. Producing semiconductor lasers with small linewidth enhancement factors requires careful attention to the problem of density of states mismatch. We calculate the linewidth enhancement factor in mid-infrared semiconductor laser active region materials and discuss the factors influencing it in each material. We show that mid-infrared, type-I, strained quantum wells have linewidth enhancement factors at the peak of the gain spectrum that are in the range of 2.5-5. These values are a factor of 1.5-3 smaller than the value for bulk alloys. However, optimized materials based on the type-II InAs/GaInSb system have linewidth enhancement factors near 1.0 due to an extreme reduction of the mismatch between the conduction and valence band densities of states. Unlike the type-I quantum wells, the peak of the differential gain lies within the region of positive gain for the type-II systems, which indicates that linewidth enhancement factors approaching zero can be obtained with DFB wavelength detuning. We present two additional optimization strategies that can be used to reduce the linewidth enhancement factor in type-II systems. Dispersion in the conduction band of a superlattice can be used to add spectral weight to the differential gain spectrum below the peak of the gain spectrum. Intentional structure in the intersubband absorption spectrum can be used to decrease the differential gain above the peak of the gain spectrum.

10:40 AM +
Carrier Recombination Dynamics of InGaSb Under Picosecond Free-Electron Laser Excitation: *R. T. Kotitschke*[1]; A. R. Adams[1]; B. N. Murdin[1]; H. Pellemanns[2]; T. Ashley[3]; G. Pryce[3]; A. D. Johnson[3]; C. T. Elliott[3]; P. C. Findlay[4]; C. R. Pidgeon[4]; [1]University of Surrey, Dept. of Phys., Guildford, Surrey GU2 5XH UK; [2]FOM Institute for Plasma Physics, "Rijnhuizen", P.O. Box 1207, Nieuwegein 3430 BE The Netherlands; [3]DERA, St. Andrews Rd., Malvern, Worcs. WR14 3PS UK; [4]Heriot-Watt University, Dept. of Phys., Edinburgh EH14 4AS UK

Recently there has been considerable interest in semiconductor lasers operating in the mid-infrared. Possible candidate materials for the fabrication of conventional mid-infrared room-temperature optoelectronic emitters and detectors are the antimonides, the lead salts and possibly the HgCdTe material system. An accurate understanding of how the recombination processes depend on carrier density is absolutely vital for emitters, which operate far from equilibrium. Although much research has been undertaken on the recombination processes, almost all was carried out in the small signal regime using photoconductivity techniques with relatively long pulse or cw radiation, where the material under investigation is only slightly being perturbed from its equilibrium state. However, recent papers on the lead salts and HgCdTe system involved high power, direct interband pump-probe techniques. This is the method used in this study. We present direct measurements of radiative and nonradiative recombination in epilayers of $InGa_xSb$ (x=0%, 5%, 10%, 20%) far from equilibrium at temperatures ranging from 30K-300K. The epilayers had a thickness of 2mm and were grown by MBE on (100) GaAs substrates. The pump-probe transmission experiments were performed on a picosecond time scale using the free electron laser facility, FELIX, in Utrecht. The photon energy chosen was far above the fundamental absorption edge, typically between 10%-40%. This excitation energy determines the quasi-Fermi-level separation at transparency since the pump intensities are sufficient to fill all lower energy band states. The broad wavelength tuneability and high pump intensities allowed a wide range of carrier densities to be studied. The near bleaching of the absorption for photon energies near to the band edge (6.8mm to 4.3mm) ensures that the carrier density is uniform throughout the epilayer being excited and the surface effects are therefore negligible. The absorption of the probe pulse, arriving after a controlled delay, was used to determine the remaining carrier density. Instead of fitting a single exponential lifetime to the response, a sophisticated model has been developed that allows the excited carrier density to be found unambiguously from the optically induced absorption change. The analysis was then performed by comparing the measured behaviour with that predicted by the model using accurate theoretical recombination rates. Those include Shockley-Read-Hall recombination, radiative recombination (CB-HH, CB-LH transitions) and Auger1 and Auger7 recombination. Our results exhibit a strong dependence of the carrier concentration decay time on Ga composition. The temperature dependence of the carrier lifetime was found to decrease with increasing Ga content irrespective of the pump intensity. The lifetimes were generally long even at high excitation intensities and were determined to be between 0.5ns and 1.2ns. Our results will be compared with data obtained previously on the HgCdTe and PbSe systems showing the variation of the Auger coefficient C with temperature, which is crucial for the design of lasers for room-temperature operation.

11:00 AM
Optical and Structural Studies of InAsSb/AlInAsSb Quantum Wells for Use in MID-IR Lasers: *Philip D. J. Calcott*[1]; Trevor Martin[1]; Martin T. Emeny[1]; Michael J. Kane[1]; David J. Wallis[1]; Gerald Williams[1]; [1]Dera Malvern, Electr. Div., St. Andrews Rd., Great Malvern, Malvern, Worcs. WR14 3PS UK

Antimonide-based III-V semiconductors are of increasing interest for Mid-infrared lasers with applications that include military systems, trace gas detection, pollution monitoring and spectroscopy. One possible active region in such lasers involves the use of strained InAsSb wells within AlInAsSb barriers. In this paper we will report a systematic study of the properties of MBE-grown InAsSb/AlInAsSb wells in which, in addition to variations in growth conditions, we have varied both the well thickness and the number of wells. Photoluminescence, transmission electron microscopy, X-ray diffraction and secondary ion mass spectroscopy have all been used to characterise the grown structures. The optical emission characteristics have then been correlated with well thickness, the number of wells and the associated strain. Results from the combined analysis also provide valuable data on the run to run repeatability of the MBE growth technique for this complex ternary/quaternary system. Finally the experimental optical emission charcteristics of our structures will be compared with theory and as appropriate, the laser performance obtained using such quantum-well active regions.

11:20 AM
Fabrication of a 3-D Simple Cubic Infrared Photonic Crystal: *Lisa Zavieh*[1]; Theresa S. Mayer[2]; [1]The Pennsylvania State University, Intercollege Mats. Eng. Program, 121 Elect. Eng. East, University Park, PA 16802 USA; [2]Penn State University, Dept. of Elect. Eng., 121 Elect. Eng. East, University Park, PA 16802 USA

It has been predicted theoretically that photonic crystals can be used to control the propagation of light through dielectric media for wavelengths extending beyond the microwave to include the infrared and the visible [1]. Fabrication of 3-D photonic crystals with a bandgap in the near infrared or visible would have application in the design of a new class of photonic devices that include optical mirrors, waveguides, and cavity resonators. To date, demonstrations of 3-D photonic crystals have been limited primarily to the microwave and infrared wavelength regimes because of the constraints imposed by the nanometer scale dimensions required for operation in the visible. The approaches that have been used to fabricate 3-D photonic crystals typically rely on applying micro-machining techniques were dielectric rods comprised of silicon or polysilicon are etched and aligned to the previous layers. Although this approach has yielded excellent results for structures where the periodicity is in the micron range, the precise layer-to-layer alignment limits the ability to scale the photonic crystals to smaller dimensions. In this talk, we present a novel method of fabricating the simple cubic photonic crystal proposed and simulated by Sozuer and Haus [2] with a periodicity of 3.5 mm and an air-to-dielectric fill factor of 0.81. In this process, we employ nonselective dry etching and selective wet

etching of a multilayer $Al_{0.6}Ga_{0.4}As/GaAs$ structure to eliminate the need to perform a layer-to-layer alignment. The fabrication begins by patterning an array of squares onto an epitaxial layer structure consisting of two periods of 2.5 mm undoped $Al_{0.6}Ga_{0.4}As$ and 1.0 mm undoped GaAs. This pattern is transferred into the epitaxial layers using magnetically enhanced reactive ion etching, with $SiCl_4$ as the reactive gas. The conditions that yield high etch rates and anisotropic profiles are optimized using design of experiment techniques resulting in the following process parameters: flow rate of 5 sccm $SiCl_4$, pressure of 10 mTorr, and power of 400 W. The final step involves selectively removing portions of the $Al_{0.6}Ga_{0.4}As$ layers with a diffusion-controlled lateral etch in a 10% HF solution. Characterization of the photonic lattice is performed using a Bruker Equinox 55 Fourier transform infrared spectrometer (FTIR) with a mid-IR source, KBr beamsplitter, and a DTGS detector. By comparing the transmission at normal incidence through the photonic bandgap structure to that of an unetched sample consisting of the epitaxial layer structure alone, we observe a decrease in the transmission of approximately 10 dB for wavelengths between 6.7 and 17.5 mm. This result corresponds well to the theoretically predicted photonic band gap, calculated to be complete for all orientations between 8.9 and 9.3 mm. The angular dependence of the bandgap is measured by varying the incident angle from 90 to 130 degrees using a Brewster angle transmission accessory. As the sample is rotated from normal to oblique angles, the center of the gap changes from 12.1 to 11.6 mm, and the high wavelength shoulder of the spectra shifts from 17.5 to 16.6 mm. These results suggest the presence of a complete photonic band gap in this square-rod simple cubic photonic crystal. 1. Yablonovitch, E., J. Opt. Soc. Am. B., 10 (2), 283 (1993).2. Souzer, H. S. and J. W. Haus, J. Opt. Soc. Am. B., 10 (2), 298 (1993).

11:40 AM
InXGa1-xAs/AlyGa1-yAs/AlzGa1-zAs Asymmetric Step Quantum Well Mid-Infrared (3-5.3um) Detectors: *Wen-Gang Wu*[1]; [1]University of California, Los Angeles, Device Research Lab., Elect. Eng. Dept., 56-125B EIV, Box 951594, Los Angeles, CA 90095-1594 USA

An optimized InxGa1-xAs/AlyGa1-yAs/AlzGa1-zAs asymmetric step quantum well structure is employed for fabricating mid-infrared (3–5.3 m) detectors with a black-body detectivity of 1.0×1010cm·Hz1/2/W at 77K and biases of 7V. The detectors display both photovoltaic-type response and bias-controlled modulation of the peak position of the photocurrent response which results from the intersubband transitions between local ground states and the global first excited states (1→2 ISBTs) in the quantum wells. At 77K and zero bias, the photocurrent spectra of the devices show a strong peak response at about 5 m which is ascribed to the 1→2 ISBTs, and their dark current and black-body detectivity have values of 2×10-10A and 0.85×109cm·Hz1/2/W, respectively. When a positive bias is applied, the photocurrent peak intensity decreases with increasing bias till approaches to nearly zero, with both the dark current and black-body detectivity reaching the minimum, at biases of 0.5V to 0.75V. These results indicate that a built-in electric field, which is believed to be caused by the asymmetry induced in the MBE growth process, exists in the active multilayer structure. The field makes the devices demonstrate a photovoltaic-type response. Based on the normalized photocurrent response spectra of the detectors, the Stark shifts of the 1→2 ISBTs in the InxGa1-xAs/AlyGa1-yAs/AlzGa1-zAs asymmetric step quantum wells are investigated. The peak wavelength of the response located around 5 m decreases gradually as the positive bias increases, which presents the blue Stark shift of the 1→2 ISBTs, while it increases gradually as the negative bias decreases, which presents the red Stark shift of the 1→2 ISBTs. The tuning between 6V and 5V of the applied bias brings about the change of the peak position of the response within the range from 1945cm-1 to 2045cm-1 correspondingly, which means more than 10meV of the total of the Stark shifts of the 1→2 ISBTs. Since the resistance and breakdown voltage of the detectors are larger than 200M and 20V, respectively, at 77K, it sound reasonable that the maximum total of the Stark shifts can reach several dozen meV. In addition, the Stark shifts of the 1→2 ISBTs in the InxGa1-xAs/AlyGa1-yAs/AlzGa1-zAs asymmetric step

quantum wells are also calculated theoretically by expanding the electron wave function in terms of normalized plane wave basis within the framework of the effective-mass envelope-function theory. The well width, barrier thickness and other structure parameters, which are used in the calculation, are got by double crystal x-ray diffraction measurement of the sample. The obtained results agree very well with the corresponding experimental measurement.

Session O. Issues for Ferroelectric and High Permittivity Thin Film Materials

Thursday AM   Room: Santa Barbara Harbor
July 1, 1999   Location: University Center

Session Chairs: Laura Wills, Hewlett Packard Laboratories, Palo Alto, CA USA; Paul McIntyre, Stanford University, Dept. of Mats. Sci. & Eng., Stanford, CA USA

8:20 AM   *Invited
Modeling of Oxide Materials for Memory Applications: *Rainer Waser*[1]; [1]IFF, Research Center, Julich D-52425 Germany

The modeling of electronic materials and devices takes place on three different levels: 1. the device functions which are linked to the electronic circuit, 2. the solid state physics which relates the microscopic and the macroscopic properties, and 3. the processing which is employed to build up the material and the device. On all three levels, the Si based semiconductor technology today extensively relies on comprehensive models implemented in detailed simulation tools. Due to the much higher complexity in composition and structure as well as the huge spectrum of functions, the modeling of electronic oxide materials and devices is still in an infant state. Currently, we see a trend to enhance the efforts of modeling of electronic oxides mainly to support the numerous activities of integrating this class of materials into the Si world. This review will cover selected examples which demonstrate the present state-of-the-art. Emphasis will be placed on the understanding of the statics and dynamics of the ferroelectric polarization as well as on properties which origin in the defect structure of the perovskite lattice which are relevant for high density memory applications. The review will attempt to identify fields of large improvements in recent years, "white" areas of lack of understanding, and trails which might be employed for an anticipation of future developments.

9:00 AM
The Effect of Thickness on the Dielectric Properties of Thin Epitaxial Films of BaTiO3: *Soma Chattopadhyay*[1]; Andrew Teren[1]; Brent H. Hoerman[1]; Jin-Ha Hwang[1]; Thomas O. Mason[1]; Bruce W. Wessels[1]; [1]Northwestern University, Mats. Sci. & Eng. Dept., Mats. Sci. and Life Sciences Bldg., 2225 N. Campus Dr., Evanston, IL 60208 USA

The dielectric properties of thin ferroelectric films have been shown to depend on film thickness for films of the order of 100 nm or less. In this study the effect of film thickness on the dielectric permittivity for thin epitaxial films of $BaTiO_3$ on MgO substrates was investigated. The films were prepared by low pressure metalorganic chemical vapor deposition. The thickness of the films ranged from 15 to 450 nm. The dielectric properties of the films were measured over the temperature range of 25 to 300°C using a heating and cooling rate of 1°C per minute to study the nature of the ferroelectric to paraelectric phase transition. The room-temperature dielectric constant decreases from 950 for a 420 nm thick film to 120 for a 15 nm thick film and the loss factor was found to decrease from 0.041 to 0.005 for the films, respectively. Concurrently the ferroelectric to paraelectric phase transition was ob-

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served to become increasingly diffuse with decreasing film thickness. The T_c decreased from 192°C for the 420 nm thick film to 111°C for the 45 nm thick film. A film with a thickness of 15 nm showed no observable transition. The observed size dependence for the thin films is similar to that observed for ferroelectric fine particles. The behavior is attributed to the coherency strain developed at the film-substrate interface.

9:20 AM

Non-Stoichiometry Accommodation and Properties in (BaxSr1-x)Ti1+yO3+z Thin Films Grown By Chemical Vapor Deposition: *Susanne Stemmer*[1]; Stephen K. Streiffer[2]; Nigel D. Browning[1]; C. B. Parker[3]; Angus I. Kingon[3]; [1]University of Illinois at Chicago, Phys. Dept., 845 W. Taylor St., Chicago, IL 60607-7059 USA; [2]Argonne National Laboratory, Mats. Sci. Div., 9700 South Cass Ave., Bldg. 212, Argonne, IL 60439-4838 USA; [3]North Carolina State University, Dept. Mats. Sci. and Eng., Raleigh, NC 27695-7919 USA

Polycrystalline thin films of (BaxSr1-x)Ti1+yO3+z (BST) are potential candidates as high permittivity dielectrics for very large scale integrated capacitor applications. It has been found that the (Ba+Sr)/Ti ratio strongly affects most film properties at a given ratio of Ba/Sr and deposition temperature and is therefore used to date to control many of the electrical properties of the films, at the expense of some reduction in film permittivity. A necessary step in understanding the composition dependence of film properties is to determine the locations within the microstructure at which excess titanium is accommodated in such fine-grained BST thin films. We use electron energy loss spectroscopy (EELS) in a field-emission transmission electron microscope to analyze changes in chemistry and local atomic environment for films grown with different titanium excesses, ranging from y=0.04 to y=0.15 in the notation used above. An incoherent lattice resolution Z-contrast image is used to position the probe on grain boundaries or in grain interiors, and to ensure a probe size of smaller than 0.4 nm for the EELS analysis. EELS shows that in the samples with high titanium excess (e.g. y=0.15), titanium segregates to the grain boundaries. Spectra recorded at the grain boundaries of the y=0.15 samples contain features characteristic for TiOx. Analysis of EELS edge fine structure shows that, even in the most titanium rich samples, the octahedral coordination of titanium with oxygen is maintained in the grain boundaries as well as in the grain interior. However, EELS within the grains indicates that these octahedra are increasingly distorted with increasing titanium content. This indicates that excess titanium is incorporated partially in the grain interiors with increasing y, although all of these samples contain total nonstoichiometry well beyond equilibrium solid-solubility limits. In addition, we determine the changes in the high-frequency dielectric properties of the grain interior by EELS, as a function of titanium excess. We will also analyze the implications of these microstructural findings for the films' dielectric and electrical properties. By employing a mean-field description of ferroelectric behavior, the dependence of permittivity, as determined using standard electrical techniques, on excess Ti can be accurately quantified and separated from the confounding effects of film thickness and measurement temperature. These results will be compared to the local dielectric functions determined by EELS to help distinguish grain and grain boundary contributions to the macroscopic permittivity. Similarly, we have previously studied leakage currents in these samples as a function of Ti composition. Models of the leakage behavior will be evaluated in terms of the levels of titanium accommodation at grain boundaries versus within the grains as estimated from TEM, in an attempt to determine if titanium enrichment of grain boundaries is a sufficient explanation for observed changes in electrical properties with y.

9:40 AM

A Mass Spectral Study of the Surface Decomposition Chemistry of Precursors for Chemical Beam Epitaxy of Lithium Niobate: *Dovas Saulys*[1]; Vladimir Joshkin[2]; Mikhail Khoudiakov[1]; Arthur Ellis[1]; Thomas F. Kuech[3]; Leon McCaughan[4]; [1]University of Wisconsin, Dept. of Chem., Rm. 7303, 1101 University Ave., Madison, WI 53706 USA; [2]University of Wisconsin, Mats. Research Sci. & Eng. Ctr., Rm. 1111, 1415 Eng. Dr., Madison, WI 53706 USA; [3]University of Wisconsin, Dept. of Chem. Eng., 1410 Eng. Dr., Madison, WI 53706 USA; [4]University of Wisconsin, Dept. of Elect. & Comp. Eng., 1415 Eng. Dr., Madison, WI 53706 USA

ABO3 ferroelectrics (e.g., lithium niobate) possess a rich variety of electro-optic, opto-mechanical, and electro-mechanical attributes not shared by semiconductors. Expanding on the limited commercial success these materials have achieved to date will require overcoming limitations in material purity, growth rates, and doping protocols. Ultimately, however, a viable thin film methodology would permit the design and production of new devices with unique capabilities. Unfortunately, thin film ferroelectrics grown by chemical vapor deposition (CVD) exhibit variable crystallinity, as well as growth rates that are too low for many practical applications (e.g., integrated optics). Overcoming these deficiencies will require knowledge of the surface decomposition chemistry of the organometallic precursors employed. We have therefore examined the surface decomposition chemistry of four common CVD precursors, the diketonates, Li(tmhd) and Nb(tmhd), and the alkoxides, Li(OBu^t) and Nb(OEt)$_5$, using chemical beam epitaxy with in-situ mass spectrometry. The absence of gas phase reactions as well as the amplified dynamic range and sensitivity of in-situ diagnostics in this pressure regime greatly simplifies the study of the surface processes which underlie purity, dopant mobility, and growth rate issues. Metal diketonates, eg M(tmhd)n and metal alkoxides, eg M(OR)$_n$, are the most commonly used precursors for the CVD of metal oxides and ferrolelctrics. We determined the diketonates Li(tmhd) and Nb(tmhd)$_4$ to be unstable at low pressures and temperatures, and therefore unsuitable for CBE. We have also elucidated, for the first time, the surface decomposition modes of the alkoxide precursors Li(OBut) and Nb(OEt)$_5$. At low temperatures, Li and Nb metal oxide film growth appears to be limited by dissociation of the metal alkoxide precursor oligomers. At higher temperatures, the surface decomposition of Li(OBu^t) involves elimination of MeLi as well as an autocatalytic hydrolysis cycle, wherein water plays a crucial role (as both reactant and product) in the generation of volatile LiOH monomers that desorb from the surface. Li(O-Bu^t) + H2O ==> Li(OH) + t-BuOH t-BuOH ==> H2O + CH$_2$=C(CH3)$_2$ Nb(OEt)5 decomposes via five major inter-related pathways at elevated temperatures (T>500°C): autocatalytic hydrolysis and ethanolysis, dehydration, dehydrogenation, and formation of ethanol. MS indicates that desorption of Nb(OH)2(OEt)2 limits growth rates at higher temperatures. Thus, for both alkoxides, autocatalytic reaction with ROH (water and/or alcohol) yields volatile metal hydroxides whose desorption from the surface limits growth rates. LiNbO3 thin films grown from both parent metal alkoxides are strongly dependent on the Li/Nb precursor ratio: at 1::1 Li(OBu^t): Nb$_2$(OEt)$_{10}$, growth never exceeds ~ 100 nm/h, while a ratio of 2.3::1 yields rates greater than 300 nm/h. We have tentatively concluded that the growth of LiNbO$_3$ initially involves a reaction similar to LiOH + Nb(OR)$_n$==>Li-O-Nb(OR)$_{n-1}$ + ROH Finally, we note that preliminary X-ray diffraction of LiNbO3 thin films grown on Al$_2$O$_3$ show a strongly oriented polycrystalline structure.

10:00 AM   Break

10:20 AM   *Invited

Advanced Gate Dielectrics for Scaled CMOS: *Glen Wilk*[1]; [1]Texas Instruments, Central Research Labs, Dallas, TX75243

The area of advanced gate dielectrics has gained considerable attention recently, because technology roadmaps predict the need for a sub-20 A oxide for sub-0.1 mm CMOS, and there are significant leakage current and reliability concerns for Si0$_2$ in this thickness regime. Efforts are being focused on altering the gate stack, rather than just the gate dielectric, because most of the high dielectric constant (high-ε) materials currently being studied, including Ta$_2$O$_5$, TiO$_2$, and SrTiO$_3$, have ε-values ranging from 25 to 80, but are not thermally stable in direct contact with Si. These materials require an accompanying oxide/nitride interfacial barrier layer to minimize reaction with Si. A different materials system which may avoid the complications of additional dielectric layers and polycrystalline films associated with the above high-ε materials will also be discussed. Potential metals for single and dual gate applications will be covered.

11:00 AM
Characterization of MFIS and MFMIS Structures Using SrBi2Ta2O9 Film with SrTa2O6/SiON Stacked Buffer Layer: *Eisuke Tokumitsu*[1]; Gen Fujii[2]; Hiroshi Ishiwara[2]; [1]Tokyo Institute of Technology, Precision and Intelligence Lab., 4259 Nagatsuta,, Midori-ku, Yokohama, Kanagawa 226-8503 Japan; [2]Tokyo Institute of Technology, Frontier Collaborative Res. Center, 4259 Nagatsuta, Midori-ku, Yokohama, Kanagawa 226-8503 Japan

Recently, ferroelectric-gate transistors have attracted much attention for non-volatile memory applications. Since preparation of the ferroelectric/Si structure with good interface is extremely difficult, an insulating buffer layer is usually inserted between the ferroelectric material and Si. Hence, a metal-ferroelectric-insulator-semiconductor (MFIS) or metal-ferroelectric-metal-insulator-semiconductor (MFMIS) structure is commonly used to fabricate a ferroelectric-gate transistor. When SiO_2 is used for an 'I' layer in the MFIS and MFMIS structures, the SiO_2 thickness must be very thin, because ferroelectric materials such as $Pb(Zr,Ti)O_3$ (PZT) and $SrBi_2Ta_2O_9$ (SBT) have high dielectric constants. Otherwise, a high dielectric constant material must be used as an 'I' layer. In this paper, we report the use of $SrTa_2O_6$/SiON stacked layer as an 'I' layer in MFIS and MFMIS structures, which has an SiO_2 equivalent thickness of 3.7nm. First, after thin chemical oxide was formed on Si substrates, nitridation of the Si wafers were performed at 1050°C for 5s in NH_4 ambient. This resulted in 2nm SiON at the Si surface. Then, 30nm $SrTa_2O_6$ was formed by the sol-gel technique. The crystallization of $SrTa_2O_6$ was carried out at 900°C for 3min. For MFMIS structures, Pt floating gate was vacuum-evaporated. Next, 400nm SBT films were grown by the sol-gel technique on $SrTa_2O_6$/SiON/Si or Pt/$SrTa_2O_6$/SiON/Si substrates to fabricate MFIS or MFMIS structures. The crystallization of SBT films was carried out at 800°C for 30min in O_2. Finally, Pt top electrodes were vacuum-evaporated and the samples were annealed again at 800°C for 30min. We first confirm that the Pt/$SrTa_2O_6$/SiON/Si MIS structures exhibit normal C-V curves with no hysteresis. Relative dielectric constant of $SrTa_2O_6$ is estimated to be 110. It is found that the SiO_2 equivalent thickness of the $SrTa_2O_6$/SiON layer is only 3.7nm. This is much smaller than the SiO_2 thickness (9nm) which is unintentionally formed at the SBT/Si interface when the SBT film is directly grown on Si by the sol-gel technique[1]. On the other hand, MFIS and MFMIS structures have hysteresis loops in the C-V characteristics due to the ferroelectricity of the SBT film. Memory windows of the MFIS and MFMIS structures are 1.1 and 3.0 V, respectively. It is also found that data retention characteristics are significantly improved by using a small SBT MFM capacitor on a large Pt/$SrTa_2O_6$/SiON/Si MIS diode. A long retention time more than 1 day is expected for an MFMIS-FET which has an area ratio, S(MFM)/S(MIS), of 0.17. The details of electrical properties and demonstration of transistor characteristic s will be presented at the conference. [1] E. Tokumitsu, G. Fujii, H. Ishiwara, Mat. Res. Soc. Symp. Proc. Vol.493, 459 (1998)

11:20 AM
Process Integration of TEOS-Based SiO2 films for Inter-Layer Dielectric on Ferroelectric Capacitors: Jeong-han Kim[1]; *Yang-han Yoon*[1]; Heon-Do Kim[1]; Sam-Dong Kim[1]; Jeong-Tae Kim[1]; [1]Hyundai Electronics Industries, Co., Ltd., Semiconductor Advanced Research Div./Process Research Dept. IV, 633, Sinhae-ri, Ganam-myun, Yeoju-kun, Kyoungki-do 467-880 Korea

LP-TEOS and O3-TEOS BPSG layers deposited on SrBi2Ta2O9 capacitor film were investigated in order to understand their process effects on the ferroelectric characteristics. Our results showed that the water content level in as-deposited dielectric films was not critical as long as post annealing at 700°C followed the deposition. Short fail was measured on the ferroelectric film with LP-TEOS deposited at 710°C while good remnant polarization, i.e. high 2Pr values (18 uC/cm2 at 75*75 um2 capacitor), were consistently measured with O3-TEOS BPSG deposited at 400°C. The remnant polarizations did not degrade when boron and phosphorous concentration in O3-TEOS BPSG film was varied, although the breakdown voltage degraded with increasing the boron concentrations.

11:40 AM
Photo-Patternable Precursors to Oxide Electrodes for Ferroelectric Memory Devices: *Charles D. E. Lakeman*[1]; Adam C. King[1]; [1]TPL Inc., Specialty Materials, 3921 Academy Parkway North, NE, Albuquerque, NM 87109 USA

Noble metal such as ruthenium (Ru) and iridium (Ir) and their oxides are used as electrodes for PbZr1-xTixO3 and Ba1-xSrxTiO3 dielectric films owing to resultant improved device performance as well as their ability to protect underlying plugs from oxygen diffusion during processing. The current lack of a convenient processing technology, however, has limited the implementation of these electrode materials in devices. TPL is developing a family of solution precursors to conducting oxides that contain photosensitive ligands that cross-link on exposure to UV radiation. This approach obviates the need for separate photoresist, thereby eliminating process steps, and enables easy, low-cost patterning of otherwise difficult to pattern materials. In particular, it enables lithographic processing without the need for aggressive plasma etching that can lead to substrate damage, and that generates toxic species. We will discuss the design of solution precursors, and present data on physical, chemical and electrical characterization of blanket electrode materials, including film microstructure, crystallinity, and crystallographic orientation, and the properties of PZT films deposited onto the electrodes. In addition, issues affecting the achievable linewidth, including edge definition and feature resolution will be discussed. Application of this process to electrode systems of interest for ferroelectric memory devices will be discussed.

Session P. Ordering in Semiconductor Alloys

Thursday PM   Room: Corwin East
July 1, 1999   Location: University Center

Session Chairs: Alex Zunger, NREL, Golden, CO USA; Gerald Stringfellow, University of Utah, College of Eng., Salt Lake City, UT USA

1:30 PM
Ordered InGaAs: Low-Temperature MOVPE Growth and Polarization Dependent Electroabsorption Measurements: *Werner Prost*[1]; Jochen Spieler[2]; Peter Velling[1]; Thomas Kippenberg[2]; Peter Kiesel[2]; Jan Krauss[2]; Gottfried H. Dohler[2]; F. J. Tegude[1]; [1]Gerhard-Mercator-University Duisburg, Solid-State Electronics Dept., Lotharstraße 65, ZHO, Gebäude LT, Duisburg D-47057 Germany; [2]Friedrich-Alexander University Erlangen-Nürnberg, Institute for Technical Phys. I, Erwin-Rommel-Str. 1, Erlangen D-91058 Germany

Under certain MOVPE growth conditions a monoatomic superlattice of alternating In and Ga rich layers forms spontaneously along the $[111]_B$ directions in InGaAs. The symmetry of this ordered InGaAs results in significant changes of the electric and optical properties compared to disordered material. The band gap reduces and the valence band maximum splits at k=0. As a consequence of dipole selections rules a strong polarization anisotropy occurs for optical transitions near the band gap. These effects are already well known in GaInP, however, by using InGaAs we aim to realize optoelectronic applications compatible to the wavelength range of optical fibers. Recently, the polarization anisotropy of ordered InGaAs has been explored down to a growth temperature of T_{gr}=540°C [1]. In this work we have extended the temperature range down to T_{gr}=450°C. All $In_{0.53}Ga_{0.47}As$ layers were grown at low-pressure of 20 mbar on s.i. InP:Fe substrates tilted 0° to 6° from [100] towards [11-1]. The quality of the layers was carefully scanned using HRXRD, PL, and AFM measurements. Due to the reduced cracking efficiency the TEGa flow rate had to be increased by more than 160% while decreasing T_{gr} from 650°C to 450°C. At low temperatures a strong impact of the lattice tilt on the InGaAs compo-

sition was found. The surface morphology of the low temperature layers exhibits a surface roughness of about 2 nm as demonstrated by AFM measurements. In addition, we carried out polarization dependent electroabsorption measurements using metal-semiconductor-metal structures. To enable Schottky contacts, we provided a 50 nm thick cap layer of InP. Analyzing the Franz-Keldysh-effect, we determined the band-gap reduction and valence-band splitting in dependence of the growth parameters. The strongest ordering effects were observed for $T_{gr}= 550°C$ and a substrate tilt of 2°. Choosing higher or slightly lower temperatures yields nearly disordered material. However, at very low temperatures ($T_{gr}= 450°C$) we also found a strong polarization anisotropy, which we attribute to a different type of ordering mechanism. Our results demonstrate that the InGaAs/InP material system exhibits similar ordering effects like GaInP/GaAs. This is of high relevance for polarization sensitive devices in optical fiber applications. [1] R. Wirth, H. Seitz, M. Geiger, F. Scholz, A. Hangleiter; "Valence-band splitting and band-gap-reduction in ordered GaInAs/InP", J. Appl. Phys. 83(11), 6196 (1998).

1:50 PM

Microstructure of CuPt-B Ordered GaInAs Films: *S. P. Ahrenkiel*[1]; D. J. Arent[1]; M. C. Hanna[1]; [1]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

We discuss CuPt-B ordered microstructures in $Ga_{0.47}In_{0.53}As$ (GaInAs) films grown on singular and vicinal (001) InP substrates by atmospheric- and low-pressure metal-organic chemical vapor deposition. Transmission electron microscope (TEM) images and diffraction patterns of ordered GaInAs reveal both qualitative similarities and distinct morphological differences to $Ga_{0.51}In_{0.49}P$ (GaInP) on GaAs, which has been extensively examined by several groups. In particular, double-variant ordered GaInAs often shows stronger lateral segregation of complementary domains on singular [001] substrates than GaInP, and exhibits contiguous, isolated disordered regions located at the apices of the faceted surface topography. The near-interface region of double-variant GaInAs is only weakly ordered prior to superdomain formation, and shows little evidence of the vertically stacked lamellar structure often observed in double-variant GaInP. The boundaries of single-variant ordered GaInAs on 6°-<111>B substrates are often inclined away from the corresponding <111>B miscut/ordering direction, rather than towards <111>B as in GaInP. Both alloy systems show an increase of the mean single-variant domain size during growth. The uses of either nitrogen- or hydrogen-containing group-V carrier gas during low-pressure growth of GaInAs are also explored. The nature of antiphase boundaries (APBs) in CuPt-B ordered semiconductor alloys have remained a topic of discussion. We examine experimental TEM dark-field image contrast of APBs and provide a description of the relevant dynamical diffraction mechanisms.

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Phase Separation and Ordering Co-Existing in MOCVD InxGa1-xN: *Mark K. Behbehani*[1]; Edwin L. Piner[1]; Sandra X. Liu[1]; Nadia A. El-Masry[1]; Salah M. Bedair[2]; [1]North Carolina State University, Mats. Sci. and Eng., 232 Riddick, P.O. Box 7916, Raleigh, NC 27695; [2]North Carolina State University, Elect. and Comp. Eng., 432 Daniels, P.O. Box 7911, Raleigh, NC 27695

Most current activities and device applications of InGaN have been restricted to lower InN% due to the lack of miscibility in the InGaN ternary alloy. We have recently reported the occurrence of phase separation for InGaN films above 25% InN. It has been suggested that ordering as well as phase separation can occur to reduce the free energy of the unstable single phase. Theoretical studies have suggested that InGaN can phase separate asymmetrically into a low InN% phase and an ordered high InN% phase. Ordering of the ternary alloy has not been well studied even though it can effect both optical and transport properties of the InGaN films. InGaN films ranging from 20% - 49% InN were grown by MOCVD on an ALE AlN Buffer layer. The films were grown for 1 h at temperatures ranging from 750°C-690°C. The resulting films were between 0.5 and 1 microns thick. In these films, both ordering and phase separation were observed to exist simultaneously. Phase separation was detected by x-ray diffraction in the 49% InN sample. TEM analysis detected both phase separation and c-plane or-

dering in the 49% InN sample. Extra spots were observed under SAD which strongly suggest the presence of an ordered structure. For samples less than 25% InN only ordering was observed. Ordering was also observed under 2-beam bright field imaging. Both 1:1 and 1:3 ordered phases were observed. Ordering occurred in small domains of approximately 20 nm. These ordered domains occurred in low strain regions of the film. The 1:1 ordering was similar in structure to other reports of ordering in high InN% films. In our films, ordering was observed in the low 20% InN films even though phase separation was not identified, indicating that the ordering process reduces the free energy of the unstable single phase. The effect of growth parameters such as growth temperature, V/III ratio, and substrate orientation on both phase separation and ordering is currently being investigated. We will report on the structural properties of these ordered domains and their effect on the optical properties. We will also report on the competition between the processes of phase separation and ordering in the ternary alloy.

2:30 PM

Band Structure and Stability of Ordered Zinc-Blende-Based Semiconductor Polytypes: *Su-Huai Wei*[1]; A. Zunger[1]; S. B. Zhang[1]; Tomi Mattila[1]; [1]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

$A_{1-x}B_xC$ semiconductor alloys grown in the vapor phase often exhibit atomic ordering, manifested, e.g., by the CuPt-like structure in $A^{III}B^{III}C^V_2$ compounds (e.g., GaInP$_2$), and by the chalcopyrite structure in the $A^{IB}A^{III}C^{VI}_2$ compounds (e.g., CuInSe$_2$). Unlike classic cases of long-range order in metallurgical systems, semiconductors often show a coexistence of domains of a few types of ordered structures in the same sample. For example, nominally chalcopyrite CuInSe$_2$ exhibits CuAu-like ordered phases, while nominally CuPt-like GaInP$_2$ samples exhibit Y2-like anti-phase boundaries and orientational superlattices. By realizing that these mixed-phase ordered structures are {\it zinc-blende-based polytypes}, we have developed a first-principles approach to predict systematically the physical properties of any member of a polytype series. We show that the coexistence of CuAu-like phase in nominally chalcopyrite compounds (e.g., CuInS$_2$) are due to bulk thermodynamic effect, while the formation of polytypes in CuPt-ordered GaInP$_2$ are not. We find that due to the effective long-range layer interactions in GaInP$_2$ polytypes, type-II band alignment exists between some polytype pairs, especially when the polytypes has small domain sizes. We also find that carrier localization can be induced by anti-phase boundaries. Our results provide a natural explanation to the spatially-indirect transitions observed in multidomain ordered samples.*Work is supported by U.S. DOE, contract No. DE-AC02-83-CH10093

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X-Ray Diffraction Study of Ordering in Epitaxial ZnSnP$_2$: *Sebastien Francoeur*[1]; G. A. Seryogin[1]; S. A. Nikishin[1]; H. Temkin[1]; [1]Texas Tech University, Elect. Eng. Dept., Lubbock, TX 79409 USA

The distribution of Zn and Sn atoms in the cation sublattice of ZnSnP$_2$ can be either random or ordered. The crystallographic structures of the disordered and ordered states are known as sphalerite and chalcopyrite, respectively. Spontaneous ordering in epitaxial layers is usually very sensitive to the growth conditions, but not easy to detect. It would be advantageous to have a rapid, simple, and non-destructive characterization technique that can identify the type of ordering and quantify the degree of ordering. This work describes the characterization of epitaxial ZnSnP$_2$ by high-resolution x-ray diffraction. The samples were grown by gas source molecular beam epitaxy on GaAs substrates. Two types of samples showing high structural perfection could be obtained by varying the Sn/Zn flux ratio. The first type of sample, grown with high Sn/Zn flux ratio, shows chalcopyrite structure while the second, grown with a low flux Sn/Zn ratio, does not show any evidence of ordering. Thus, at a constant growth temperature, the Sn/Zn flux controls the degree of ordering in ZnSnP$_2$. It also affects the lattice mismatch of the epitaxial layer. Chalcopyrite ordering is determined by the observation of several characteristic reflections identifying the lower symmetry of the structure. By rotating the sample around an axis located in the diffraction plane by a specific tilt angle, any diffraction conditions can be met. The tilt angle is the angle separating

the normal to the plane (hkl) of interest and the diffraction plane. The diffraction peaks of ordered samples are found at angles calculated for the chalcopyrite structure. For example, we observe diffraction planes (1 0 1/2), (2 1 7/2), and (6 1 1/2), forbidden for sphalerite. In addition, the measured intensity distribution shows excellent agreement with the calculation. The widths of the diffraction peaks are typical of homogeneous samples and the tetragonal axis shows strong preferential alignment along the growth direction. The second type of samples does not show any evidence of chalcopyrite ordering, for all possible orientations of the tetragonal axis. These samples were also investigated for the presence of CuAu and CuPt-type of ordering of the cation sublattice, but again no evidence of ordering could be found.

3:10 PM Break

3:30 PM
Comparison of Dopants used to Control Ordering in GaInP: *Chris Fetzer*[1]; Yu Hsu[1]; Rung-Ting Lee[1]; Sung-Won Jun[1]; J. Kevin Shurtleff[1]; Gerald B. Stringfellow[1]; [1]University of Utah, Dept. of Mats. Sci. and Eng., 223 KRC, Salt Lake City, UT 84112 USA

The effect of dopants on CuPt ordering in GaInP has been studied extensively. The purpose of this paper is to compare the effects of Te, Zn, Si, and Sb doping on the step structure and degree of order of GaInP layers grown by OMVPE in an effort to clarify the mechanisms that lead to disordering during the growth process. Te doping significantly affects the surface structure and ordering of GaInP layers, but it does not change the surface reconstruction. A decrease in the degree of order occurs over the range of Te concentrations (beginning at 3×10^{-17} cm^{-3}) that give a marked increase in the step spacing. Successful growth of disorder/order/diorder heterostructures in GaInP using Te doping requires a 10 minute interuption in the growth between layers. These results suggest that Te collects at the surface. Zn doped GaInP layers become completely disordered as the Zn concentration is increased above 2×10^{-18} cm^{-3}. This correlates with a decrease in the [-1,1,0] step spacing. GaInP disorder/order/disorder structures with thin wells can not be produced by Zn doping. This supports the hyposthesis that Zn diffuses into the well, increasing the Ga and In diffusion coefficients. Doping GaInP layers with Si does not affect the surface reconstruction, but slightly affects the surface structure. The degree of order decreases as the Si concentration is increased above 2×10^{-18} cm^{-3}. GaInP order/disorder heterostructures can be produced by Si doping. The effect of Sb doping on the surface reconstruction, surface structure and ordering of GaInP layers will also be presented in this paper. Sb is expected to collect at the surface, since it has a low vapor pressure and is too large to be easily incorporated into the lattice. Sb is of particular interest, because it is isoelectronic and does not affect the fermi level. The effect of these dopants on the surface structure indicates that at high concentrations, all act as surfactants: they act to change adatom attachment at steps on the surface.

3:50 PM
Ordering and Antiphase Boundaries in Te-doped GaInP Layers Grown by Organometallic Vapour Phase Epitaxy: *T-Y Seong*[1]; C.-J. Choi[1]; S. H. Lee[2]; G. B. Stringfellow[2]; [1]Kwangju Institute of Science and Technology, Dept. of Mats. Sci. and Eng., Kwangju 500-712 Korea; [2]University of Utah, Dept. of Mats. Sci. and Eng., Salt Lake City, UT 84112 USA

Transmission electron microscope (TEM) and transmission electron diffraction (TED) have been widely used to assess CuPt ordering in (001) layers of III-V ternary alloys grown by OMVPE and MBE. CuPt ordering is believed to be a surface related phenomenon occurring during epitaxial growth. TEM dark field (DF) examination has revealed ordered domains in MBE and OMVPE III-V ternary layers. The ordered domains usually contain a density of APBs. Such APBs are reported to adversely influence the optical and electrical properties of the layers. Therefore, it is important to be able to control such defects to enhance device performance. In this work, TEM and TED studies have been performed to investigate the effects of Te-doping on ordering and antiphase boundaries (APBs) in organometallic vapour phase epitaxial GaInP layers grown on (001) GaAs singular and vicinal substrates at 670 ¡ÆC. TEM results show that the behaviour of APBs for the singular samples differs from that of the vicinal samples. The density of APBs in the vicinal samples is increased by roughly a factor of 2, whilst that of the singular samples is slightly increased, as the Te doping level increases. APBs are inclined some degrees from the [001] growth surface. For the singular samples, the angle is found to remain virtually unchanged with increasing Te concentration. However, for the vicinal samples, the angle decreases significantly with increasing Te concentration. A simple model is presented to explain the dopant concentration dependence of the behaviour of APBs in the ordered GaInP.

4:10 PM
Maximum Direct-Gap Reduction in CuPt Ordered Al$_x$Ga$_{1-x}$InP ($0 \pounds x \pounds 1$) Determined by Generalized Ellipsometry: *M. Schubert*[1]; J. A. Woollam[1]; B. Rheinlander[2]; I. Pietzonka[3]; V. Gottschalch[3]; [1]University of Nebraska-Lincoln, Center for Microelectronic and Optical Materials Research, Lincoln, NE 68588; [2]University Leipzig, Faculty of Phys. and Geoscience, Leipzig 04103 Germany; [3]University Leipzig, Faculty of Chem. and Mineralogy, Leipzig 04103 Germany

In a manner similar to biaxial strain, spontaneous CuPt ordering causes reduction of the fundamental band gap DE$_g$ (relative to the disordered compound), a crystal-field splitting D$_{cf}$ at the valence-band maximum, and an increase of the spin-orbit splitting value D$_{so}$. We have determined the ratio D$_{cf}$/DE$_g$ and D$_{so}$/DE$_g$ for the Al$_x$Ga$_{1-x}$InP system lattice matched to GaAs as a function of composition x. We investigated partially ordered samples with different compositions x and degrees of ordering h, using transmission and reflection generalized variable angle spectroscopic ellipsometry (gVASE), cross-polarized (darkfield) transmission spectroscopy (DFS), and modulated cross-polarized reflectance difference spectroscopy (cRDS). We treat the observed order-birefringence as "chemical-stress" induced piezo-birefringence. We find that the parabolic band approximations and the selection rules for the transitions from the G$_{4,5v}$, G$_{6(1)v}$, G$_{6(2)v}$ valence band states to the G$_{6c}$ conduction band states, suffice for excellent modeling of the order-birefringence in the near-band-gap spectral region. In particular, explicit treatment of the transition-matrix k-dependence (as recently reported for ordered GaInP or GaInAs) seems avoidable. The transition energies, strengths, and broadening parameters for the three zone-center transitions are obtained from analysis of the sample dielectric function tensor. All parameters in the quasi-cubic perturbation model can be fitted with the three transition energies from all samples. For alloy ratios that produce direct-gap semiconductors (i.e., for x<0.5) our results are found in excellent agreement with the linear interpolation of recent theoretical values for GaInP and AlInP by Wei and Zunger [Phys.Rev.B 57, 8983 (1998)]. For indirect-gap materials (i.e. for x>0.5) we find an almost exponential deviation from the predicted values with increasing x. These result in very large valence-band splittings for partially ordered AlInP, as reported earlier [Schubert etal., Phys.Rev.B 54, 17616 (1996)]. However, both experimentally determined ratios possess the same denominator when divided by the D$_{cf}$ and D$_{s0}$ parameters predicted by Wei and Zunger. The denominator is DE$_g$; which, in fact, is the only parameter to be revised among those calculated by Wei and Zunger. As a result, we obtain the maximum direct-gap reduction as well as the random-alloy band gap of Al$_x$Ga$_{1-x}$InP as a function of x. These dependencies now allow for immediate quantification of the degree of ordering of a partially ordered sample, regardless of its composition. We find further that the maximum gap reduction for AlInP is smaller than predicted by almost an order of magnitude. The revision of the theoretical DE$_g$ parameter appears reasonable, because Wei and Zunger used the corrected local-density approximation. This approximation tends to contain errors in the positions of the conduction bands, although it produces precise energies for the valence band states.

4:30 PM +

Observation of Type I/II Transition in GaAs/InGaP Heterostructure by C-V Profiling.: *Shouvik Datta*[1]; M. R. Gokhle[1]; A. P. Shah[1]; T. K. Sharma[2]; B. M. Arora[1]; [1]Tata Institute of Fundamental Research., Solid State Electronics Group/Dept. of Condensed Matter Phys. & Mat. Scis., Homi Bhabha Rd., Colaba, Mumbai,, Maharashtra. 400 005 India; [2]Centre for Advance Technology, Indore 452 013 India

It is known in the literature (1, 2) that InGaP alloy synthesized within a certain range of growth temperatures (520°C to 720°C) shows Cu-Pt crystal ordering. This ordering reduces the band gap energy. It is predicted that the ordering induced modification of energy levels of InGaP lowers its conduction band edge, which could change a type I band alignment at a GaAs/InGaP heterojunction to type II. Here we report the first observation of this ordering related type I/II transion for a GaAs/InGaP heterojunction by C–V profiling (3) experiments done at room-temperature. Heterostructures used in this work are prepared by MOVPE technique at substrate temperatures of 670°C and 720°C for samples A and B respectively. Flux rates of TMGa and TMIn precursors used during the growth are same in both cases. We have used n type doping (»5´1016 cm-3) for both layers in the samples. For C-V profiling measurement gold Schottky dots are deposited on the top GaAs layer and Au-Ge-Ni ohmic contacts are made on the InGaP. Figure 1 shows n(X) versus X profile for the sample A. We see an accumulation of electrons on the InGaP side of the heterojunction and a corresponding depletion region on the GaAs side. Clearly band alignment in this sample is type II, where conduction band edge of InGaP lies below that of GaAs. In comparison for sample B (figure 2) we see a depletion region on the InGaP side and accumulation on the GaAs side of the heterojunction. However, this is the characteristic of type I band alignment where the conduction band edge of InGaP lies above that of GaAs. We have also measured the photoreflectance spectra (4) of these samples. Figure 3 shows that the spectrum of sample A is rigidly shifted to lower energy as compared to sample B. This shows relatively larger alloy ordering of InGaP in sample A. Therefore, from all these results we conclude that the change of band alignment from type II in sample A to type I in sample B is caused by greater degree of ordering in sample A as compare d to the ordering in sample B. Further experiments are also in progress. References: 1) Alex Zunger, MRS Bulletin, 20, July (1997). 2) G.B.Stringfellow, MRS Bulletin, 27, July (1997). 3) H.Kroemer et.al, Appl.Phys.Lett, 36(4), 295 (1980). 4) D.E.Aspnes, Handbook of Semiconductors, Vol 2, M.Balkanski ed, (North-Holland, NY, p109, 1980)

4:50 PM   Late News

Session Q. Nanostructure Self-Assembly

Thursday PM   Room: Corwin West
July 1, 1999   Location: University Center

Session Chairs: Supriyo Bandyopadhyry, University of Nebraska, Dept. of Elect. Eng., Lincoln, NE USA; David Janes, Purdue University, School of Elect. Eng, West Lafayette, IN USA

1:30 PM

In-Situ Growth of InAs Quantum Dots on Patterned GaInAs/InP Nanostructures: Magnus Borgström[5]; Jonas Johansson[1]; Ivan Maximov[1]; *Werner Seifert*[1]; Lars Samuelson[1]; [1]University of Lund, Solid State Phys., Box 118, Lund S-221 00 Sweden

Self-assembled quantum dots can be used as the active units in device structures based on resonant tunnelling or Coulomb-blockade effects. For this purpose we have studied in MOVPE the positioning of InAs dots on top of patterned GaInAs/InP nanostructures. The base structure consists of InP(substrate)/GaInAs/InP(70 nm barrier)/GaInAs(3.5 nm etch mask). Into this structure holes of 100-200-500 nm diameter were etched, removing selectively the 70 nm InP barrier. By overgrowing the patterned surface with GaInAs/InP/InAs(2 monolayers, self-assembling into dots)/InP one obtains a structure which functions as a vertical transport device with the current flow restricted to the openings in the InP barrier layer. Conditions were found where in the concave sinks above the openings just one or two InAs dots nucleated. The process is strongly affected by the lateral anisotropy of etch rate and growth rate in the two <110> directions and the type of facets which develop at the side wall of the holes.

1:50 PM

Formation of Nanoscale Self-Assembled Si1-xGex Islands Using Chemical Vapor Deposition and Subsequent Thermal Annealing of Thin Metastable Films: *Rashid Bashir*[1]; Abul Ehsan Kabir[2]; Kuo-Jen Chao[3]; Cara L. Weitzsacker[3]; [1]Purdue University, Elect. and Comp. Eng., 1285 EE Bldg., W. Lafayette, IN 47906 USA; [2]National Semiconductor, 2900 Semiconductor Dr., MS E-100, Santa Clara, CA 95051 USA; [3]Charles Evans and Associates, 240 Santa Ana Court, Sunnyvale, CA 94086 USA

There have been numerous publications in the recent years that deal with the self-assembly of semiconductor islands on a crystalline substrate for the formation of quantum optical and electronic devices. A lattice mismatch material can be grown as a thin strained 2-D film on a substrate. Due to the strain energy of the lattice mismatch, the growth then proceeds by the 3-D Stranski-Krastanow mode in which the material will form small islands of random size and distribution. The formation of these islands on a silicon substrate is specially attractive since this would allow possible integration of these quantum devices with existing silicon devices to form novel device structures and because these self-assembled nano-scale islands could offer possibilities at the end of the silicon device scaling Road map. The Silicon-Germanium (Si1-xGex) material system is very attractive since it can be directly grown on silicon substrates. There have been recent reports on the growth of pure Ge islands on silicon using RPCVD growth techniques. In this study, we report for the first time, on the formation of self-assembled Si1-xGex islands by the selective CVD of very thin (<150Å) highly strained assembled Si1-xGex (x~0.5) films on patterned silicon wafers and the subsequent annealing of these thin films. Unlike previous studies, islands are formed during the thermal annealing of these thin films after the growth of the smooth continuous selectively grown thin film and not by direct growth of the islands. Thin (50-150Å) Si0.6Ge0.4 films are selectively grown on silicon wafers within a 3500Å oxide pattern. A commercially available epitaxial system (ASM) was used to deposit the films using chemical vapor deposition from GeH4, Si2H2Cl2, and HCl at 650°C and 40 Torr. A high temperature H2 bake was used to remove any native oxide prior to the growth. After the growth, the wafers were in-situ annealed in H2 at 750°C at 40 Torr for 6 minutes resulting in the formation of the islands. The island size was studied using an AFM (Digital Instruments) and was found to be a function of the pattern in which the selective Si0.6Ge0.4 film was grown. Grain size analysis software from Digital Instruments was used to determine the size distribution of the islands and was found to vary with the exposed silicon area. Given the above process conditions above, in a representative area, the mean grain size area was found to be 47290 nm2 (~245nm diameter) with a std. deviation of 15310 nm2 (~139nm). Cross-sectional TEM was also performed and crystal defects were found within the islands. The height of these islands could be as high as 350nm. It was found that if the wafers were exposed to room ambient right after the growth, and hence passivated with native oxide, subsequent annealing of the films at 750°C did not result in the island formation. The islands were also not formed if the anneal was done at 650°C, 40T, and in H2 for up to 25 minutes. However, if a H2 anneal at 650°C, 20T, for 6 min was performed, islands were formed with a different distribution than ones described earlier. The composition of the films before annealing and islands formed annealing was investigated using scanning auger microprobe. The germanium fraction was found to decrease to about 20% in the self-assembled islands. Hence the technique shows promise as possible way to form sub-micron device islands for future optical and electronic applications.

2:10 PM +

Fabrication and Characterization of Magnetic Semiconductors "Spin Wires" and "Spin Dots": *O. Ray*[1]; J. J. Berry[1]; A. A. Sirenko[1]; N. Samarth[1]; J. A. Gupta[2]; I. Malajovich[2]; D. D. Awschalom[2]; [1]Pennsylvania State University, Phys., 104 Davey Lab., State College, PA 16802 USA; [2]University of California, Dept. of Phys., Santa Barbara, CA 93106 USA

Studies of nanostructures fabricated from semiconductors and (metallic) ferromagnets have followed parallel but separate tracks, each motivated by an interest in manipulating factors such as the electronic density of states and magnetic ordering via reductions in dimensionality. Contemporary interest in the development of "magneto-electronics" motivates us to bridge these disparate areas by incorporating magnetic interactions directly into conventional semiconductor nanostructures. It is anticipated that the interplay between reduced dimensionality, strain and the carrier-ion exchange interaction might allow the systematic tailoring of both magneto-optical and magneto-transport phenomena in such systems. Here, we describe the development and characterization of quantum "spin wires" and quantum "spin dots" with sizes down to 20 nm, patterned from MBE-grown II-VI magnetic semiconductor quantum wells by using electron beam lithography followed by wet chemical etching. Undoped (Zn,Cd,Mn)Se single quantum well structures sandwiched between ZnSe barriers are first grown by MBE on (100) GaAs substrates. The samples are spin coated with 100 nm thick PMMA with a subsequent direct write on a Leica EBPG 5 using 50 keV electron beam energy. Multiple wire and dot fields are defined on the same sample, with an area coverage of 0.125. Following exposure and development in a mixture of MIBK:IPA, a 15 nm titanium layer is evaporated to serve as a hard mask. After lifting off the hard mask, wet etching with a mixture of potassium dichromate and diluted hydrobromic acid leads to pattern transfer onto the semiconductor template, resulting in spin wires and spin dots with sizes ranging from 150 nm down to 20 nm. Structural characterization of the patterned samples using scanning electron microscopy and atomic force microscopy allows us to relate the pattern definition, size, etch depth and the overall surface quality to variations in processing techniques. Low temperature (T ~ 5 K) photoluminescence studies reveal the influence of the patterning/processing on both intrinsic and extrinsic effects (e.g. defect formation). Shifts in the luminescence can be correlated to an interplay between strain relaxation and quantum confinement. In the larger structures, a red shift is observed, suggestive of a partial strain relaxation. Finally, we will also report on the results of ongoing magneto-PL studies that probe the effect of patterning on the carrier-ion exchange interactions through the measurement of the exchange-enhanced Zeeman splitting. Work supported by NSF grants DMR-9701484 and -9701072 and ONR grants N00014-99-1-0071 and N00014-99-1-0077.

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Preparation and Characterization of Gold-Platinum Nanorods: Sa Huang[1]; Benjamin Martin[2]; Daniel Dermody[2]; Thomas Mallouk[2]; Thomas Jackson[1]; *Theresa Mayer*[1]; [1]Penn State University, Elect. Eng., 121 Elect. Eng. East, University Park, PA 16802 USA; [2]Penn State University, Dept. of Chem.

Self-assembly techniques are of interest for electronic and optoelectronic device integration at the micro- and nano-scale. An application that has gained attention recently utilizes the complementary nature of DNA base pairs to selectively attach III-V emitters and detectors to a host silicon substrate. Whereas this approach allows precise placement of micron-scale devices onto a dissimilar substrate, these techniques can also be applied to the assembly of three-dimensional nanostructures where traditional semiconductor fabrication procedures are difficult to implement. For example, assembly of a simple woodpile structure consisting of alternating layers of perpendicularly oriented nanorods made from polymers or metals could be used to fabricate 3-D photonic crystals or memory devices. In this talk, we describe the preparation and characterization of colloidal Au, Au-Pt, and Au-Pt-Au nanorods that are being developed for use in a 3-D high-density memory structures. Such Pt tipped Au nanorods can be self-assembled into 3-D structures by derivitizing the Au tips with amine terminated thiols or with complementary single-strand DNA. The metal nanorods used here were grown electrochemically in aluminum oxide nanopore membranes [1] with sonication used to improve the mass transport of metal ions into the pores, and to allow the gases liberated by the plating process to migrate out of the pores. To characterize Au, Pt, and Au-Pt nanorods, they were transferred from a liquid carrier to an insulating SiO_2 substrate where large-area plated Au bonding pads were added for electrical probing. Prior to dispersing the rods onto the substrate, a thin 100-nm Cr/100-nm Ag seed metal layer was deposited on the SiO_2 substrate to facilitate electroplating of the Au bonding pads. The bonding pads were defined lithographically by aligning pads to the two rod-ends and opening 100 "100 mm^2 windows in 3.0 mm thick photoresist. Organic contamination was removed using a low-power oxygen plasma. The rods were secured by electroplating a 1.5 mm thick layer of Au using the photoresist windows as a plating mask. Following plating, the photoresist mask was dissolved and the seed metal was removed selectively. The resistivity of Au and Au-Pt nanorods was determined by measuring the current-voltage characteristics using an HP 4155 semiconductor parameter analyzer. For both rod types the resistivity was 2 "10^{-5} W-cm, approximately one order of magnitude higher than that of bulk Au. This indicates that the resistivity is limited by the nanostructure of the plated metal rather than the interface between the metals.[1] C. R. Martin, Chemistry of Mats., 8, 1739 (1996).

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Self-Assembly of Patterned Films of Nanometer-Diameter Gold Clusters that are Linked by Organic Molecules: *Jia Liu*[1]; Ronald P. Andres[1]; [1]Purdue University, Dept. of Chem. Eng., 1283 Chem. Eng. Bldg., West Lafayette, IN 47097-1283 USA

Self-assembly fabrication is one way to achieve high density nanoscale structures for electronic and optoelectronic applications. One such self-assembly scheme that has been proposed is the casting of a monolayer film of metal clusters onto a flat solid substrate followed by introduction of an organic molecule that bonds to the clusters and physically and electronically joins adjacent clusters in the film to each other to form a molecularly linked superlattice [1]. Such a linked cluster network has many attractive properties the foremost being: 1) if the clusters have diameters in the 2-6 nm size range, their Fermi levels and electronic density of states are close to that of the bulk metal while their low intercluster capacitance gives rise to correlated single electron tunneling between clusters and 2) the electronic conductance of the film can be controlled by the choice of the organic linking molecule. In order to construct interesting electronic devices, however, methods must be developed to fa bricate predetermined patterns of cells and interconnects of the linked clusters. We have developed a method for fabricating patterned films of linked clusters on the surface of a substrate. The key steps in this scheme are: 1) self-assembly of a continuous linked cluster film on a water-based liquid surface, 2) fabrication of a lithographically defined pattern of areas on the surface of a solid substrate where the energy of adhesion of the cluster film is high and areas where the adhesion energy is low, 3) transfer of the intact cluster film from the liquid surface to the solid substrate, and 4) removal of those portions of the film that are not strongly held to the substrate by solvent rinsing. The critical step in this process is self-assembly of the initial linked cluster film. Gold clusters, which have uniform diameters of 4-5 nm and which have been encapsulated by alkane thiol molecules (e.g. 1-dodecanethiol) are dispersed in a nonpolar organic solvent. Casting this colloidal suspension on a water-based liquid surface and allowing the solvent to evaporate, produces a hexagonal close-packed monolayer of clusters floating at the air-liquid interface. The clusters in the film are then bonded to each other by organic linking molecules which are dissolved in the supporting liquid. Repeated casting of the colloidal suspension onto the liquid surface produces a mutilayer film. Once a uniform linked film has been self-assembled on the liquid surface, it is transformed into a patterned film on the substrate as described above.[1] Andres, et al., Sci. 273, 1690 (1996)

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Directed Self-Assembly of Metal/Semiconductor Structures for Nanoelectronic Devices and Circuits: *Brian L. Walsh*[1]; M. Batistuta[1]; Takhee Lee[2]; Jia Liu[3]; Q. Qu[3]; E. H. Chen[1]; R. P. Andres[1]; D. B. Janes[1];

R. Reifenberger[2]; [1]Purdue University, School of Elect. and Comp. Eng., West Lafayette, IN 47907; [2]Purdue University, Dept. of Phys., Lafayette, IN 47907; [3]Purdue University, School of Chem. Eng., West Lafayette, IN 47907

Self-assembly techniques are of interest because they can provide high density nanoscale structures without high resolution lithography. Various structures have been realized by self-assembly including semiconductor quantum dots and 1-D and 2-D arrays of metal nanoclusters.[1] However, conventional self-assembly approaches suffer from several problems which limit their applicability for forming interesting electronic devices. First these techniques yield uniform networks without the cells/interconnect structures required to achieve computational functions. In addition, networks of metal islands or isolated semiconductor quantum dots are not sufficient by themselves to provide functionality. At present, it is not possible to realize the types of structures typically used in integrated circuits (transistors, arbitrary interconnect structures) using self-assembly based approaches. However, it has been shown that computational functionality can be realized by networks of nanoscale metallic nodes which have been arranged into specific cell and interconnect structures, provided that each metallic node is coupled to a two-terminal semiconductor active device to provide a nonlinear, nonmonotonic I-V relationship (e.g. a resonant tunneling diode characteristic).[2] We have developed a directed self-assembly approach which provides nanoscale elements which are organized into structures required for useful electronic circuits and which have been integrated onto a semiconductor device layer. The specific structure consists of close-packed arrays of 4 nm diameter Au clusters which are selectively deposited within regions on a low-temperature-grown GaAs surface coated with an organic tether molecule (xylyl dithiol). The deposition regions are defined using an elastomeric stamp pad which has been lithographically defined with the desired pattern. In the present demonstration, these regions are at the micron scale, however, the technique should be capable of providing deep submicron regions. The local organization of the metal nanoclusters is provided by the self-assembly process, which provides a means to realize well organized nanoscale structures without nanometer scale lithography. This approach allows structures of interest (cells, interconnects) to be defined for a hybrid electronic device/circuit structure containing nanoscale metallic nodes and active device regions which have been organized into the structures required to provide desired circuit functionality. The tether monolayer also forms an effective etch mask for the LTG:GaAs substrate under standard wet chemical etching, making it possible to use both the regions coated with xylyl dithiol and, possibly, the individual nanoclusters, as "in-situ" masks for patterning the semiconductor device regions. These developments provide a means to realize nanoelectronic circuit using high-throughput fabrication techniques. [1] R.P. Andres, et al. Sci. 272, 1323, (1996). [2] V.P. Roychowdhury, S. Bandyopadhyay, D. B. Janes, IEEE Trans. on Electron Devices, 43, 1688 (1996).

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Dry-Etched Grating in the MQW Active Layer for DFB Laser Arrays Fabrication: *Talneau Anne*[1]; Bouadma Nouredine[1]; Slempkes Serge[1]; Ougazzaden Abdallah[1]; [1]OPTO+, France Telecom/CNET, Route de Nozay, Marcoussis 91460 France

We present an attractive technological approach for DFB laser array fabrication which combines the high uniformity of RIBE dry-etching and the high throughput of holographic exposure for grating fabrication. Complex-coupled DFB laser structure with periodically etched quantum wells allows high monomode yield and deterministic position of the emitted wavelength as far as the same grating geometry is realised for all the lasers. For first order coupling in 1.55μm emitting DFB lasers, grating pitches are around 240nm. The holographic set-up was designed to allow grating period accuracy better than 0.1nm. Moreover, RIBE dry-etching which has already demonstrated a very high depth uniformity and accuracy is preferred. As RIBE etching of InP related materials erodes the resist holographic mask, a dielectric mask is defined by lift-off of the resist. The grating is etched in the two upper wells of a ten MQW strain-compensated active layer. As fine anisotropic etching with low damage and contamination is required, a very low-ion energy RIBE etching -50eV- was used in order to limit degradation of the etched wells materials. These RIBE conditions have been optimised with the help of carrier lifetime measurements. After etching and chemi-

cally cleaning the active material, the measured carrier lifetime is reduced by only a factor of 3 from the unprocessed material. A thin InP layer (100nm) was then regrown on this patterned active layer to embed the grating and allow further laser processing steps on a flat surface. AP-MOVPE regrowth conditions have been optimised in order to obtain a dislocation-free InP regrown layer and no degradation of the grating shape, as observed by TEM. The laser structure is a BRS one with lateral proton implantation. Emitted wavelength uniformity measured on a eight DFB laser array demonstrates the advantages of this technology: two-section lasers were measured, with as cleaved facets. Threshold currents are in the range 10-13mA when biasing only the front section. The deviation to the mean value of the spacing within the array is as low as 15GHz. This discrepancy can be overcome using the electrical tunability when biasing the rear section, leading to an exact 100GHz spacing. This work was supported by the European ESPRIT NANOLASE project.

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Various AFM Nano-Oxidation Processes for Planar Type Single Electron Transistor: *K. Matsumoto*[1]; Y. Gotoh[1]; T. Maeda[1]; [1]Electrotechnical Laboratory, 1-1-4, Umezono, Tsukuba-shi, Ibaraki-kenn, 305 Japan

For the room-temperature operation of the single electron transistor (SET), the planar type structure was proposed by us and realized using the AFM nano-oxidation process. The process oxidized the surface of 2nm thick titanium metal which sat on the atomically flat a-Al_2O_3 substrate using the AFM can tilever as an ultra-small cathode, and formed the oxidized titanium (TiO_x) line which works as a tunnel junction for the single electron transistor. So far, the width of the TiO_x line, i.e., the width of the tunnel junction was as fat as 30nm, and the resulting drain current of the SET became as small as of the order of 10-15A and included a large noise. For the improvement of the SET characteristic, the increase of the tunnel current is indispensable. Therefore, the reduction of the TiO_x line width has been important issue. For this purpose, following trials war examined, i.e., (1) pulse bias was used for the oxidation instead of DC bias, (2) the humidity of the AFM chamber was precisely controlled, (3) contact-mode carbon nanotube cantilever was applied. By adopting the pulse bias to the cantilever, the aspect ration of width and depth of the oxidized titanium line was improved twice. This is because during the oxidation process, the positive hydrogen ion was produced and formed the positive space charge at the front end of the titanium oxidation that prohibits the further oxidation. When the negative pulse bias was applied to the metal, the positive space charge was neutralized and the oxidation becomes possible again. Therefore, using the pulse bias, the deeper oxidation becomes possible and aspect ratio is improved. Using this process, the width of the TiOx line becomes less than 20nm, typically 15nm. Further improvement of the oxide width is realized by combining the pulse bias process and the humidity control. Using this method, the TiOx line width of 10nm was realized. The apex of the cantilever also play an important role for the fabrication of the narrow oxide wire. The conventional apex of the cantilever is 10-20nm which limits the size of the oxide wire. The narrower the apex of the tip, the narrower oxidized line will be expected. For this purpose, the contact mode carbon nanotube cantilever was examined. The multi-wall carbon nanotube was attached to the conventional contact mode cantilever by glue, and used as a ultra small cathode for the oxidation of the metal. Using this special cantilever, the oxide line width of 10nm is also attained even in the air ambience. The single electron transistor with the tunnel oxide barrier of 19nm was fabricated. The SET shows the drain current of the order of 10-12A which is three orders of magnitude higher current than the previous one. The increase of the drain current owing to the narrower tunnel junction width improves the S/N ratio and the SET shows the clear Coulomb oscillation with the periods of 2.1V at room-temperature.

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Semiconductor Patterning Techniques Based on Self-Assembled Structures: *M. V. Batistuta*[1]; D. B. Janes[1]; B. Walsh[1]; J. Liu[1]; Q. Qu[1]; R. P. Andres[1]; E. L. Peckham[1]; E. -H. Chen[1]; [1]Purdue University

Fabrication techniques developed to obtain nanoscale devices must combine the desired functionality with high throughput. This requires

the processing of a large quantity of interconnected molecular size structures at the same time, on a suitable device substrate. One approach, which can provide such interesting structures, is the use of chemically self-assembled nanostructures. While such techniques are typically applied on inert substrates, the application of these techniques to semiconductor device structures could provide the basic building blocks required for higher density computational networks. One example of a self-assembly technique applied to semiconductor fabrication is the use of self-assembled monolayers (SAM's) of organic molecules as ultrathin resists for e-beam nanolithography [1]. Reported etching results using SAM resists on stoichiometric GaAs show incomplete protection of the GaAs surface, which can be attributed to the relatively rapid oxidation of the GaAs and the corresponding lack of chemical stability of the SAM's on the surface. The present work involves the patterning of GaAs device layers using two types of masking techniques based on chemical self-assembly. The first technique involves deposition of pattern regions of a Xylyl Dithiol SAM using an elastomeric stamp pad technique. A two step selective chemical etching technique is then used to obtain controlled etching depths of a few nanometers per iteration. A surface layer of low temperature grown GaAs (LTG:GaAs), which oxidizes more slowly than stoichiometric GaAs, has been used to obtain more stable SAMs on the GaAs surface and therefore more effective protection from the etchant. Since the thin (3-5 nm) LTG:GaAs layer provides electronic passivation of the surface, a shallow etch is sufficient to effectively pattern devices. While similar in principle to the electron beam lithography using SAM resists, this technique offers an effective etch protection mask with a higher throughput than e-beam nanolithography. Initial demonstrations have been at the micron scale, but there is evidence that the technique can be extended to deep submicron dimensions. The second technique involves nanometer scale patterning using uniform size gold nanoclusters as etch masks on GaAs device layers. Initial experiments have used 20nm clusters which are tethered using dithiol SAMs on layer structures capped with LTG:GaAs. By applying appropriate etching techniques, it is possible to etch a mesa beneath each cluster, resulting in an in-situ metal contact over the semiconductor mesa. While initial experiments have utilized isolated clusters, it is possible in principle to use more complicated configurations obtainable from self-assembly, including 1-D or 2-D arrays of nanoclusters, as the in-situ masks. The resulting metallic islands and semiconductor device mesas could provide unit cell structures for functional device architectures. [1] D.W. Carr, M.J. Lercel, C.S. Whelan, H.G. Craighead, K. Seshadri and D.L. Allara, J. Vac. Sci. Technol. A 15, 1446-50 (1997).

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Thermo-Mechanical Properties of Polymers for Nanoimprint Lithography: *Thomas Hoffmann*[1]; Frank Gottschalch[1]; Clivia M. Sotomayor Torres[1]; [1]BUGH Wuppertal, Institute of Mats. Sci., Gauss-Str. 20, Wuppertal 42097 Germany

Nanoimprinting is based on embossing a rigid stamp with an appropriate surface relief into a viscoelastic polymer above its glass transition temperature. Under the applied pressure the polymer starts to flow below the elevated stamp features and fills the recessed areas of the stamp. It has been shown that the technique is capable to produce features as small as 10 nm and nanodevices such as single electron transistors. Despite these promising results a number of questions have to be answered to evaluate the application of the technique for mass fabrication. One of these questions arises from the successful transfer of patterns over large areas (some cm[2]) which is related to the flow properties of the polymer thin films (typically less than 1 µm thick). It is known from nano-indentation measurements in polymer thin films that the presence of an underlying rigid substrate such as silicon affects the mechanical properties, e.g., the hardness. Therefore, we expected that the viscoelastic properties which define the material flow during imprinting differ from that of the bulk. In bulk materials the irreversible deformation (flow) on indentation depends on the molecular weight and the temperature of the polymer. We carried out a study comparing the indentation in bulk samples of poly(methylmethacrylat) (PMMA) of different molecular weight with the imprint of features in thin films of the same polymers. Indentation of bulk samples with molecular weights in the range from 50,000 to 810,000 were carried out in a range of temperature between the glass transition (T^g) and $T^g + 40°C$ by

means of a thermo-mechanical analyzer (TMA). For all molecular weights it is observed that the irreversible part of deformation increases with increasing temperature. The ratio between the irreversible (flow) and the reversible part (recovery) of deformation depends strongly on the molecular weight. The low molecular weight polymer shows the largest irreversible part of deformation for a given temperature difference with respect to T^g. Although the results of imprints into thin films were only qualitatively evaluated by scanning electron microscopy (SEM) no similar tendency was observed. Independent of the molecular weight good flow was obtained only at imprint temperatures of 80°C above the glass transition. It seems that flow is much more affected by the presence of the rigid substrate underneath the polymer thin film rather than by the molecular weight itself. This clearly would set constraints to the nanoimprinting technique as a relatively high temperature is required for good pattern transfer. On the other hand, a high molecular weight may be chosen with no need to apply higher temperatures and better etching stability may be obtained.

Session R. Properties of InGaN Heterostructures and Devices

Thursday PM   Room: Lotte Lehman Hall
July 1, 1999   Location: Music Building

Session Chairs: Joan Redwing, Epitronics, Phoenix, AZ USA; Christian Wetzel, Meijo University, High Tech Research Center 1-501, Shigomaguchi Tenpaku-ku, Nagoya, Japan

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Single-Mode Nitride-Based Laser Diodes Using Thick n-AlGaN Layers: *T. Takeuchi*[1]; N. Hayashi[1]; M. Iwaya[1]; K. Isomura[1]; K. Kimura[1]; M. Yamaguchi[1]; T. Detchprohm[1]; S. Yamaguchi[1]; C. Wetzel[1]; H. Amano[1]; I. Akasaki[1]; S. Watanabe[2]; Y. Yamaoka[2]; R. Shioda[2]; T. Hidaka[2]; Ys. Kaneko[2]; Yw. Kaneko[2]; N. Yamada[2]; [1]Meijo University, Dept. of Elect. and Electr. Eng., Nagoya 468-8502 Japan; [2]Hewlett-Packard Laboratories, 3-2-2 Sakado, Takatsu-ku, Kawasaki 213-0012 Japan

It is quite difficult to grow crack-free thick AlGaN on GaN due to the large lattice mismatch between AlGaN and GaN. In order to prevent cracking, conventional nitride-based laser diode (LD) structures often have AlGaN cladding layers with insufficient AlN mole fraction (about 5%) and thickness (about 0.5microns) to effectively confine the optical mode. This leads to optical leakage from guiding layer into the underlying n-GaN layer, resulting in lower optical confinement and a multi-peak far field [1]. In this paper, we propose a new LD structure in which thick n-AlGaN is used instead of thick n-GaN. We first investigated the AlGaN layers directly grown on low-temperature-buffer/sapphire substrates by metalorganic vapor phase epitaxy. The thickness of AlGaN layers was about 1micron, and the AlN molar fractions were up to 0.2. From the X-ray measurements, we found that these AlGaN layers were fully relaxed, while AlGaN layers in AlGaN/GaN heterostructures were under tension [2]. Moreover, the AlGaN layers grown directly on the low temperature-buffer had very few cracks. Next, we grew GaInN quantum well LD structures including the thick n-AlGaN cladding layers. This structure had also very few cracks, even though it had 4micron-thick n-AlGaN with an AlN mole fraction of 7%. We also found that the n-AlGaN cladding layer was fully relaxed and other layers were coherently grown on the underlying n-AlGaN. This means that there was no tensile strained layer, which prevented the generation of cracks in these LD structures. Both the far field pattern and the near field pattern of this new LD showed a clear single peak. This result indicates sufficient optical confinement in this new LD structure. The threshold current of this laser structure was around 300mA, which is comparable to that of conventional laser structures

with an n-AlGaN/n-GaN/LT-buffer/sapphire structure, indicating that high quality layer structures can be obtained on AlGaN/LT-buffer structures. This work was partly supported by the Ministry of Education, Sci., Sports and Culture of Japan (High-Tech Research Center Project and contract nos. 07505012, 09450133, 09875083) and 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 Buffer Layer at the Interface in a Highly-Mismatched System". [1] D. Hofstetter et al., Appl. Phys. Lett. 70(1997)1650.[2] T. Takeuchi et al., Jpn. J. Appl. Phys. 36, L177 (1997).

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Violet-Blue InGaN/GaN MQW Light Emitting Diodes on Epitaxially Laterally Overgrown GaN.: *Koen Jacobs*[1]; Wim Van der Stricht[1]; Ingrid Moerman[1]; Piet Demeester[1]; Steven Verstuyft[1]; Joël De Nayer[1]; Peter Van Daele[1]; Amal Amokrane[2]; Sophie Dassonneville[2]; Brigitte Sieber[2]; Edward J. Thrush[3]; [1]University of Gent, Inform. Tech. - IMEC, Sint-Pietersnieuwstraat 41, Gent B-9000 Belgium; [2]Université des Sciences et Technologies de Lille, Laboratoire de Structure et Propriétés de l'Etat Solide, UPRESA 8008, Bâtiment C6, Villeneuve d'Ascq Cédex 59655 France; [3]Thomas Swan & Co, Ltd., Unit 1C, Button End, Harston, Cambridge CB2 5NX UK

We report on the fabrication of GaN-based light emitting diodes using epitaxially laterally overgrown GaN (ELOG) substrate layers, grown by organometallic vapour phase epitaxy (OMVPE) on c-plane sapphire in a vertical rotating disk reactor. The active region of the LEDs is positioned between a Si-doped n-type GaN layer and a Mg-doped p-type GaN layer, and consists of an $In_xGa_{1-x}N$/GaN multi quantum well structure, with x varying between 0.15 and 0.2. Reactive ion etching was used to expose the n-type GaN, whereas the metal contacts consisted of AuGe/Ni for the n-type layer, and Ni/Au or Ni/Pt/Au for the p-type layer. The applied ELOG layers were investigated by various characterisation techniques, such as cross-sectional transmission electron microscopy (TEM), X-ray diffraction (XRD), photoluminescence (PL) and cathodoluminescence (CL). TEM indicated a substantial reduction of the threading dislocation density, resulting in overgrown areas, which are virtually dislocation free. Hence, improved optical and structural properties were obtained: PL revealed a decrease of the yellow luminescence, CL emission was much more intense for the overgrown regions, and finally XRD evidenced an enhanced crystalline quality by means of a reduction of the rocking curve FWHM by 20%. This quality progress was reflected in an enhancement of the ELOG LED performance, compared to conventionally grown LEDs. Not only the usually observed decrease of the leakage current was encountered under reverse bias conditions, but also an increase of the output power by at least a factor of 40 was discovered, as opposed to what other groups report [1]. This might indicate that in our case threading dislocations do act as non-radiative recombination centers in the conventional LEDs on (0001) sapphire, with a carrier diffusion length, which is large enough for the carriers to be trapped by the dislocations, due to a shorter average distance between these defects. Under normal circumstances, such defects do not act as non-radiative centers, because as a result of the more ionic character of the nitrides and the In-composition fluctuation, efficient exciton localization occurs, i.e. the carriers can not travel far enough to encounter the dislocations [2]. The InGaN-based LEDs exhibit a typical turn-on voltage of 6 V and an operating voltage of 8 V at 20 mA. These high voltages are mainly caused by the non-optimized p-type contacts, which still show Schottky behaviour. Progress was already made by using Ni/Pt/Au contacts instead of Ni/Au contacts for the p-type GaN layer, which resulted in a decrease of the turn-on voltage towards 4 V. Further optimization of these contacts is expected to give rise to a significant improvement of the device efficiency. [1] T. Mukai et al., Japanese Journal of Applied Phys., Vol. 37 (1998), pp. L839-L841. [2] S.D. Lester et al., Applied Physics Letters, Vol. 66(10), (1995), pp. 1249-1251.

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Dislocation Reduction in GaN Epilayers via Lateral Overgrowth from Trenches: *Y. Chen*[1]; S. Y. Wang[1]; R. S. Kern[2]; C. H. Chen[2]; C. P. Kuo[2]; [1]Hewlett-Packard Company, Hewlett-Packard Laboratories, 3500 Deer Creek Rd. MS26U-12, Palo Alto, CA 94304; [2]Hewlett-Packard

Company, Optoelectronics Div., 370 West Trimble Rd., San Jose, CA 95131

Blue and UV laser diodes have been produced recently by metalorganic chemical vapor deposition (MOCVD) with lateral epitaxial overgrowth (LEO). The dislocation density is reduced in the LEO GaN epilayers to improve the laser performance. In our experiments, we have demonstrated a new way to reduce the dislocation density by lateral overgrowth from trenches (LOFT). In LOFT, trenches are etched in GaN thin films first. The bottoms of the trenches and the surfaces of the mesas are then masked with silicon dioxide, so that the regrowth of GaN thin film is forced to initiate from the trench sidewalls. Since the threading dislocations formed in the original growth tend to be parallel to the sidewalls, they are therefore basically "dislocation free" substrate for regrowth. The advantage for LOFT over LEO is that the dislocation density is reduced over the whole wafer within one regrowth. The structures of the GaN grown by LOFT has been studied by TEM, SEM, and AFM etc. Our TEM observation indicates that the dislocation density is reduced dramatically in the LOFT GaN layers. Electronic and optical properties of the LOFT GaN based materials and devices will also be discussed.

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Measurement of Crystallographic Tilt in the Lateral Epitaxial Overgrowth of GaN: *Paul T. Fini*[1]; James P. Ibbetson[2]; Hugues Marchand[2]; Lijie Zhao[1]; Steven P. DenBaars[1]; James S. Speck[1]; [1]University of California, Santa Barbara, Mats. Dept., Bldg. E-II, Santa Barbara, CA 93110 USA; [2]University of California, Santa Barbara, ECE Dept., Bldg. E-I, Santa Barbara, CA 93110 USA

Lateral epitaxial overgrowth (LEO) has recently been shown to significantly reduce extended defect density in GaN films grown on sapphire by metalorganic chemical vapor deposition (MOCVD). However, some difficulties remain in controlling the structural quality of the overgrown material. For example, in the LEO of GaN from <1 -1 0 0> - oriented stripes in an SiO_2 mask it has been observed in transmission electron microscopy (TEM) that the "wings" (overgrown GaN) exhibit crystallographic tilts away from the "window" (seed) regions. Wing tilt may cause significant problems when coalescence of neighboring LEO stripes occurs, since coalescence fronts take the form of double-angle tilt boundaries, and may be sources for additional dislocation generation. Obviously a desirable result would be the elimination of wing tilt altogether, as it would enable the fabrication of large-area devices such as LEDs and lasers without regard to the underlying stripe orientation and spacing. In this presentation, x-ray diffraction (XRD) is demonstrated as a straightforward means of measuring wing tilt in LEO from stripes. Specifically, an w rocking curve about the 002 peak is performed, with the scattering plane perpendicular to the stripe direction. In this study, LEO of GaN on an SiO_2 mask was performed simultaneously on <1 -1 0 0>-oriented stripe patterns of various "fill factors" (ratio of stripe opening width in mask to stripe period), since it has been shown that fill factor has a direct influence on stripe morphology. Additionally, the growth parameters of temperature and input V/III ratio were varied, as they are also known to affect the manner in which the stripes grow. The effects of these parameters on the degree of wing tilt measured by XRD are shown and correlated with TEM and scanning electron microscopy (SEM) of stripes in cross-section. For the "baseline" growth conditions in this study, tilts on the order of 1-2° are measured, and increase with increasing fill factor. When the growth temperature is increased by 40℃, wing tilt increases (< ~4°), and is higher for higher fill factors as well. However, when the V/III ratio is lowered to half of that of the baseline conditions, little or no discernable tilt is measurable for the range of fill factors studied. These results are explained in the context of an energy balance between the LEO GaN/SiO_2 interface and the free stripe facets, which are dependent on growth conditions and pattern geometry. The authors wish to acknowledge funding support from the Office of Naval Research (IMPACT MURI, C. Wood) and the Air Force Office of Scientific Research (G. Witt).

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MOCVD Growth and Characterization of AlInGaN Quaternary Alloys: *Michael E. Aumer*[1]; S. F. LeBoeuf[1]; F. G. McIntosh[1]; Y. C. Chang[1]; J. F. Muth[1]; R. M. Kolbas[1]; S. M. Bedair[1]; [1]North Carolina State

University, Dept. of Elect. and Comp. Eng., Box 7911, Raleigh, NC 27695 USA

Recent advances in III-nitride knowledge have allowed both the commercialization of nitride-based devices and the demonstration by several groups of room-temperature cw operation of a nitride based laser diode. Despite these successes resulting from progress in the growth of the ternary alloys AlGaN and InGaN, relatively little is known of the properties of the quaternary alloy $Al_xIn_yGa_{1-x-y}N$. Growth of high quality quaternary alloys enhances the experimental capability to investigate the role of strain and piezoelectric effects in GaN-based quantum wells and allows fabrication of lattice matched active layers. Sample growth was performed in a modified Thomas Swan MOCVD system. A 350 angstrom ALE-style AlN buffer layer, followed by 2 microns of MOCVD GaN were deposited before quaternary layer growth. The $Al_xIn_yGa_{1-x-y}N$ layer was grown at temperatures between 780°C and 875°C at atmospheric pressure in a vertical reaction chamber. The precursors used for this study were ammonia, trimethylgallium, trimethylaluminum, and trimethylindium. Purified nitrogen was used as the carrier gas. The band gap of the samples was determined from transmission measurements and PL, the lattice constant was extracted from XRD data, and chemical composition was confirmed through EDS. A series of samples was grown based on the growth conditions necessary for high quality $In_xGa_{1-x}N$ (x = 0.08 to 0.16). The Al flow varied from 0.06 to 0.15 micromols/min, and the Ga flow varied from 1 micromol/min for high temperature growth down to 0.7 micromols/min for growth at 780°C. The In flow was changed to maintain a constant 10:1 ratio of In to Ga. These conditions resulted in $Al_xIn_yGa_{1-x-y}N$ films with compositions in the range of x=0 to 0.2 and y=0 to 0.16. Growth of high quality quaternary alloys was confirmed by the presence of band edge PL. It was found that quaternary growth must occur at temperatures much higher than those required to obtain high quality InGaN; otherwise, the PL spectrum is dominated by deep level emission. However, the elevated temperature necessitates a redesign of the growth parameters such as growth rate, precursor molar ratios, and ammonia flow, in order to incorporate a significant percentage of indium. Growth parameters for $Al_xIn_yGa_{1-x-y}N$ lattice matched to GaN are reported, and material properties for the unstrained bulk are compared with data for strained thin films. Mercury probe C-V measurements demonstrate the presence of a 2D electron gas at the GaN-$Al_xIn_yGa_{1-x-y}N$ interface. Preliminary data is reported on the properties of lattice matched unstrained $Al_xIn_yGa_{1-x-y}N$/InGaN double heterostructures. The successful growth of device quality quaternary alloys will permit fabrication of several lattice matched device structures which are not feasible for the current highly strained structures.

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3:30 PM

Behavior of Quantum Well Excitons under Internal Fields of GaN/AlGaN and InGaN/GaN/AlGaN Quantum Well Structures: *Shigefusa F. Chichibu*[1]; Takahiro Deguchi[2]; Takayuki Sota[2]; Steven P. DenBaars[3]; Shuji Nakamura[4]; [1]Science University of Tokyo, Elect. Eng. Dept., Faculty of Sci. and Tech., 2641Yamazaki, Noda, Chiba 278-8510 Japan; [2]Waseda University, Dept. of Elect., Electr., and Comp. Eng., 3-4-1, Ohkubo, Shinjuku, Tokyo 169-8555 Japan; [3]University of California, Santa Barbara, Mats. and ECE Depts., Santa Barbara, CA 93106-5050 USA; [4]Nichia Chemical Industries, Research and Development Dept., 491 Oka, Kaminaka, Anan, Tokushima 774-8601 Japan

Major developments of III-nitride semiconductors have led to the commercial production of quantum well (QW) structure blue/green LEDs and to the sample forwarding of LDs lased at 400 nm with lifetimes more than 10,000 hours. InGaN alloys are attracting special interest because they form active regions of UV, blue, green, and amber SQW LEDs and MQW LDs. The emission mechanisms in InGaN are not yet fully understood due to complex material physics and Eng., such as phase separation or compositional inhomogeneity due to large mismatches in the lattice constants, vapor pressure, and optimum growth temperature between GaN and InN, large effective masses and polarization due to the wurtzite crystal lattice. In this presentation, fundamental electronic modulations and decay dynamics in strained AlGaN/GaN and InGaN QWs are treated to explore the reason why InGaN devices emit bright luminescences in spite of the large threading dislocation (TD) density up to 10^10 cm-3. Effects of the internal electric field, F,

across the QW, which is a sum of the fields due to spontaneous and piezoelectric polarizations and pn junction field, on the quantized energy levels are described to show how F changes them. Indeed F causes the redshift of the QW resonance through the quantum confined Stark effect (QCSE). Even under such high F stronger than 500 kV/cm, a 5-nm-thick GaN SQW exhibited a clear excitonic absorption peak even at room-temperature (RT). Despite this fact, spontaneous emission intensity of the GaN SQW is very low; the structure does not exhibit stimulated emission. Conversely, slightly In-alloyed GaN SQW (InGaN UV LED) exhibited bright UV emission and showed the stimulated emission from the edge. The absorption spectrum of strained InGaN QWs is further modulated by quantum-confined Franz-Keldysh effect and bulky Franz-Keldysh effect from the barriers when the potential drop across the well (FxL) exceeds the valence band discontinuity, dEv. This produces apparent Stokes-like shift in addition to the in-plane net Stokes-like shift due to the potential inhomogeneity in InGaN QWs. Under large FxL with L larger than the 3D exciton Bohr radius aB, e-h pair is confined in opposite sides of the well resulting in reduced wavefunction overlap. However, the quantum confinement is enough provided that L<aB, and effective in-plane localization of the QW excitons in quantum disk size potential minima, which are produced by nonrandom alloy potential fluctuation enhanced by the large bowing parameter and F, is found to play an important role to produce efficient emission. The InGaN amber SQW LEDs with InN mole fraction larger than 0.23 suffers from huge piezoelectric field, but exhibit reasonable efficient emission since L<aB.

3:50 PM

Piezoelectric Effects in the Radiative Centers of GaInN/GaN Quantum Wells and Devices: *Christian Wetzel*[1]; Tetsuya Takeuchi[1]; Hiroshi Amano[1]; Isamu Akasaki[1]; [1]Meijo University, High Tech Research Center, 1-501 Shiogamaguchi, Tenpaku-ku, Nagoya, Aichi 468-8502 Japan

Identification and control of the electronic band and defect structure in GaInN/GaN wide band gap heterostructures is of pivotal relevance for the design of high efficiency light emitting devices and power electronics. In groundbreaking works, a large number of experimental evidence has been presented that show features typically associated with structural inhomogeneities, defects, and impurities. For example large discrepancies of band gap energies and emission wavelengths have been reported, wavelength shifts depending on excitation power or Dr. current, as well as spatial inhomogeneities of emission energy, intensities and contrasts in electron microscopy. On the other hand, high total and differential efficiencies for radiative emission would characterize those defects as very beneficial for high device performance and worthy special consideration and discussion. To this end, we have employed photoluminescence under variable conditions, photomodulated, and electromodulated reflection to GaInN single heterostructures, GaInN/GaN quantum wells, and device structures. By a detailed analysis, abundant information on the radiative centers is directly obtained. We take into account that large pseudomorphic strain in uniaxial wurtzite layers with partly ionic bonding conditions induces very large piezoelectric effects. From well-resolved Franz-Keldysh oscillations in the spectral reflectivity, we very accurately determine the magnitude of electric fields acting in GaInN single heterostructures. Fields up to 1 MV/cm are identified which has significant consequences on the electronic states of impurities and other radiative centers in the well. Similar very clear signature is seen in the case of GaInN/GaN quantum wells. Here we find a clear correlation of the derived electric field values and several transitions including the maximum of the luminescence. We find that to a very good approximation all transition energies are very well described considering the quantity of the piezoelectric dipole moment across well. This concept bears strong similarities to Wannier-Stark ladders in AlGaAs/GaAs systems with the important distinction that in the present case the width of the barrier is not apparently a relevant parameter. The role of the electric field in the transition energy is further identified by its variation in an externally applied bias field. Besides a shift of the emission, energy previously assigned to the quantum confined Stark effect we observe a bias field controlled splitting of the levels associated with the luminescence. This again indicates that the centers of radiative emission are strongly controlled by the quantity of the electric field. Altogether, this renders

valuable details on the highly efficient radiative centers. This work was partly supported by the MESSCJ and JSPS.

4:10 PM
Phase Separation in InGaN/GaN MQWs: *L. T. Romano*[1]; M. D. McCluskey[2]; T. Suski[3]; J. Jun[3]; [1]Xerox Palo Alto Research Center, 3333 Coyote Rd., Palo Alto, CA 94304 USA; [2]Washington State University, Dept. of Shock Phys., Pullman, WA 99164-2814 USA; [3]Unipress, UI, Sokolowska 29, 01-142 Warsaw, Poland

Phase separation of InGaN is an important topic related to the possibility of forming "localized states" in nitride blue lasers. Annealing experiments were performed on $In_xGa_{1-x}N$/GaN MQW samples, grown by MOCVD, as a function of both temperature and nitrogen overpressure for compositions in x up to 0.30. The nitrogen pressures that were used ranged from atmosphere pressure up to 15 kbar at temperatures between 950°C - 1400°C. It was found by TEM that phase separation only occurred under conditions that produced voids within the MQWs. Void formation could be suppressed at high nitrogen overpressures (15 kbar) and subsequently phase separation did not occur. The phase separation was correlated to an In-rich peak observed in XRD and a low energy peak observed by optical absorption. For sufficiently high temperature (1400°C) at 15 kbar, interdiffusion of the wells and barriers occurred rather than void formation or phase separation. These results suggest the difficulty in bulk phase separation of InGaN. A simple model explaining these results will be discussed.

4:30 PM +
Role of Below Bandgap States in the Radiative Emission of InGaN/GaN Quantum Well Structures: *Georgiy O. Vaschenko*[1]; Milan S. Minsky[2]; Dinesh Patel[1]; Luiz S. Assis[1]; Robert L. Pidcock[1]; Carmen S. Menoni[1]; Stacia Keller[2]; Evelyn L. Hu[2]; Steven P. DenBaars[2]; [1]Colorado State University, Dept. of Elect. Eng., Fort Collins, CO 80523 USA; [2]University of California, Santa Barbara, Dept. of Mats. Eng. and Elect. and Comp. Eng., Santa Barbara, CA 93106 USA

The physics underlying the radiative emission in InGaN/GaN multiple quantum well (MQW) structures impacts the design of light emitting devices. The main features of the radiative processes in these structures are explained with different models which emphasize the effect of localization of carriers on In alloying fluctuations, self-formation of InN quantum dots, and the spatial separation of carriers by piezoelectric fields. We present evidence that the main radiative emission band in the InGaN/GaN MQW structures arises from recombination via energy states localized 100-200 meV below the bandgap. The main signatures of such deep level emission are a large Stokes shift and decay times exceeding 10 ns. The origin of the broad distribution of deep energy states could be associated with either indium composition fluctuations and/or the presence of extended and point defects in the MQWs. Two sets of $In_xGa_{1-x}N$/GaN samples were investigated. One set consisted of 4 samples with x varying between 10 and 16 % and identical Si doping of ~ 2×10^{18} cm^{-3} in the barriers. Another set was composed of 5 samples with x fixed at 20 % and Si doping in the barriers ranging from 10^{17} to 3×10^{19} cm^{-3}. All structures were grown on c-sapphire substrates with a 2 mm GaN buffer layer and consisted of 3 nm wells separated by 7 nm barriers. The samples were characterized by time integrated and time resolved photoluminescence (PL), and absorption measurements. PL spectra were taken in a wide range of excitation power densities, and sample temperatures ranging from 11 to 350 K. The common feature of all the samples is a broad (on the order of 90-200 meV) PL spectrum where the PL peak is red shifted by >100 meV with respect to the absorption edge. The Stokes shift is larger for the samples with high In concentration and for the samples with small Si doping in the barriers. Increasing the Si concentration in the barriers gradually blue shifts the PL peak emission and absorption edge. The PL exhibits decay times in the range of 1 - 20 ns depending on the sample, and short rise times of 10 - 30 ps. Both the decay and the rise time are longer in the samples with larger Stokes shift. Our experiments also show that within the PL emission band the decay time is dependent on the detection energy, being longer for detection energies below the PL peak. Increasing the In composition broadens the energy distribution of the deep states, leading to broader PL, and longer lifetimes. The introduction of Si into the barriers affects the deep level emission by reducing the density of deep states through improvement of the sample

morphology [1]. As a result, the decay time shortens, the PL peak blue-shifts and the PL efficiency increases, reaching its maximum value for a Si doping concentration of ~ 2×10^{18} cm^{-3}. The work at UCSB is supported by QUEST NSF Sci. and Technology Center and at CSU by the National Sci. Foundation. [1] S. Keller, S.F. Chichibu, M.S. Minsky, E. Hu, U.K. Mishra, S.P. DenBaars, J. Crystal Growth vol. 195, (1998) 258.

4:50 PM +
Optical Band Gap Dependence on Thickness and Composition of InGaN Grown on GaN: *Christopher Arlen Parker*[1]; Mason J. Reed[2]; John C. Roberts[1]; Sandra X. Liu[2]; N. A. El-Masry[2]; S. M. Bedair[1]; [1]NC State University, Elect. and Comp. Eng., 232 Daniels Hall, Box 7911, Raleigh, NC 27695 USA; [2]NC State University, Mats. Sci. and Eng., 232 Riddick Labs., P.O. Box 7916, Raleigh, NC 27695 USA

While much attention has been directed toward the properties of thin pseudomorphic InxGa1-xN used as active layers in optical devices, the properties of thicker, unstrained InxGa1-xN films are not well known. Often, the band gap (Eg) of relaxed InxGa1-xN films is deduced from measured band gaps of strained films by utilizing elastic properties of GaN to calculate the band gap shift due to a deformation potential. Direct experimental measurements of unstrained InxGa1-xN films for a wide range of x can alleviate any controversy in these deduced band gaps. We report on the optical properties of unstrained InxGa1-xN films grown on a GaN pre-layer on sapphire substrates by atmospheric MOCVD. Variance of x is achieved by varying the growth temperature between 750°C and 820°C while holding the organometallic fluxes constant. The InxGa1-xN films investigated have values of x between 0 and 0.25 as determined by X-ray diffraction (XRD) and thicknesses up to 1 mm determined by cross-sectional TEM. Off-axis double crystal X-ray diffraction (DCXRD) verifies that the films are unstrained. Photoluminescence (PL) is employed to determine the optical band gap of these relaxed films and an experimental band gap bowing parameter of 3.8 eV for unstrained films is determined. This value is based on relaxed films with a much wider range of x than previously reported values for strained films. We also find that the optical properties as determined from PL depend on the thickness of the film and can be characterized by three regions. For very thin InxGa1-xN films, the measured optical band gap is comparable to strained films reported in the literature. For very thick InxGa1-xN films, the optical band gap of these unstrained films is independent of thickness. However, a third intermediate region is observed where the PL data is dominated by deep level emissions which are not consistent with the PL data of the other two regions. The rationale for the dependence of the optical band gap on thickness and the value x will be discussed and the nature of defects in the three regions will be reported.

Session S. Silicon Carbide Processing for Devices

Thursday PM   Room: Multicultural Center Theater
July 1, 1999   Location: University Center

Session Chairs: Michael A. Capano, Purdue University, School of ECE, W. Lafayette, IN USA; Tom Jackson, Penn State University, University Park, PA USA

1:30 PM
Phosphorus and Nitrogen Implantation into 4H-SiC: *Michael A. Capano*[1]; Rajkumar Santhakumar[1]; Mrinal K. Das[1]; James A. Cooper[1]; Michael R. Melloch[1]; [1]Purdue University, School of Elect. and Comp. Eng., 1285 Elect. Eng. Bldg., West Lafayette, IN 47907-1285 USA

Many SiC electronic devices require selective doping of epitaxial layers that can only be achieved by ion implantation. However, ion implantation processing has been identified as a cause of low carrier mobilities in the inversion channel of metal-oxide-semiconductor field effect transistors (MOSFET). As an example, the inversion layer mobility of 4H-SiC MOSFETs built on implanted p-wells are typically less than 1 cm^2/Vs. When built on p-type epilayers, similar MOSFETs have higher mobilities, but they are usually less than 10 cm^2/Vs. Inversion-layer mobilities are known to increase with decreasing annealing temperature needed to activate the n-type source/drain implant. Improved transport characteristics of 4H-SiC MOSFETs may be realized if appropriate implantation and annealing procedures are identified that facilitate low-temperature (<1400°C) processing while maintaining good dopant activation. In this presentation, results from nitrogen and phosphorus implantation experiments on 4H-SiC are discussed, in an effort to determine which element is the best choice for MOSFET source/drain definition. In 4H-SiC implanted with 3 x 10^{15} cm^{-2} nitrogen ions, the minimum sheet resistance observed is 534 W/sq. The minimum sheet resistance in 4H-SiC implanted with 4 x 10^{15} cm^{-2} phosphorus ions is 51 W/sq, a record low value for any implanted element into SiC. Time-independent sheet resistances are observed following high-temperature annealing at 1700°C for both nitrogen- and phosphorus-implanted samples. Annealing at temperatures below about 1500°C cause sheet resistances to monotonically decrease with increasing duration of anneal. Most significant in terms of device performance, the sheet resistances measured from phosphorus-implanted 4H-SiC are an order of magnitude lower than those measured from nitrogen-implanted samples. The response of phosphorus to low-temperature annealing is outstanding, and sheet resistances below 500 W/sq are achieved at 1200°C. Because the low annealing temperature characteristics of phosphorus-implanted 4H-SiC are so appealing, the behavior of phosphorus-implanted 4H-SiC in an oxidizing atmosphere, both with and without prior implant activation anneals, is examined to determine how readily phosphorus can be incorporated into SiC MOSFETs. A three-hour gate oxidation in wet O$_2$ at 1150°C, followed by a 30 min argon anneal, yields a sheet resistance of 1081 W/sq without an implant activation anneal. However, the oxide growth rate over an implanted source/drain region was a factor of five faster than over an unimplanted channel. Activation annealing prior to gate oxidation reduced the oxide growth rate dramatically. Sheet resistances tended to increase by about 20% following oxidation compared to samples subjected solely to activation anneals. Mobility test structures which incorporate phosphorus implantation technology are in process as of the writing of this abstract. Results from these mobility tests, plus reasons for the disparity between nitrogen and phosphorus implants, are to be presented.

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Hydrogen Passivation of Aluminum and Boron Acceptors in SiC by Low Energy ion Implantation: *Norbert Achtziger*[1]; Christian Huelsen[1]; Wolfgang Witthuhn[1]; Margareta K. Linnarsson[2]; Martin Janson[2]; Bengt G. Svensson[2]; [1]University Jena, Institut fuer Festkoerperphysik, Max-Wien-Platz 1, Jena D- 07743 Germany; [2]Royal Institute of Technology, Solid State Electronics, Electrum 229, Kista-Stockholm S-16440 Sweden

Hydrogen is known to passivate electrically active centers in various semiconductors. In silicon carbide, hydrogen incorporation is known to happen during CVD growth, but systematic reports about intentional H passivation are rare (for references, see [1,2]). Generally, hydrogen diffusion is strongly trap-limited. To achieve a well-controlled incorporation of hydrogen, we are using implantation of hydrogen with very low energy (300 eV per atom) to avoid self-trapping at implantation defects. In p-type SiC, this results in a strong passivation of acceptors (B and Al). In contrast to the very small range of the implanted ions in the order of 10 nm, the passivation takes place on a micrometer depth scale already at an implantation temperature of 300 K, i.e. hydrogen is highly mobile. The chemical concentration profiles of hydrogen and the profiles of passivated acceptors (B, Al) are closely related. Parts of these results are already published [1,2]. In the present contribution, we additionally report on the influence of implantation temperature (300...680 K), ion fluence and of the sample's doping level on the degree of passivation and on the thickness of the passivated layer. All experiments are done on epitaxial (CVD) layers. The techniques used are Capacitance-Voltage (CV) profiling, admittance spectroscopy, Deep Level Transient Spectroscopy (DLTS) and Secondary Ion Mass Spectrometry (SIMS). A reduction of the electrically active acceptor concentration by up to 3 orders of magnitude is detected. The thermal stability of acceptor-hydrogen complexes is probed by annealing experiments: for aluminum, the dissociation is observed in the temperature range between 510 K and 570 K resulting in an estimate of the binding energy (1.75 eV). For boron, no dissociation has been found up to now. There is clear evidence for an ion drift of hydrogen under the influence of the electrical field in a Schottky diode. This proves that hydrogen preferentially exists as a positive ion. In addition to the shallow acceptor states, there is also a passivation of the deep level related to the boron D-center; its concentration is reduced by a factor of at least 20. Deep levels in n-type material, however, were not affected under similar conditions. References: [1] N. Achtziger, J.Grillenberger, W. Witthuhn, M. K. Linnarsson, M. Janson, B. G. Svensson, Appl. Phys. Lett. 73(7), 945 (1998) [2] N.Achtziger, C.Hülsen, W.Witthuhn, M. K. Linnarsson, M. Janson, B. G. Svensson, phys. stat. sol.(b) 210, 395 (1998)

2:10 PM +

Effect of Implant Activation Annealing Conditions on the Inversion Channel Mobility in 4H- and 6H-SiC MOSFETs: *Mrinal Kanti Das*[1]; Michael A. Capano[1]; James A. Cooper[1]; Michael R. Melloch[1]; [1]Purdue University, School of Elect. and Comp. Eng., 1285 Elect. Eng. Bldg., West Lafayette, IN 47907-1285 USA

The ability to thermally grow SiO$_2$ makes MOS devices feasible on SiC. Efforts in optimizing the MOS interface using the MOS-C test structure has resulted in Q$_F$ and D$_{IT}$ in the mid 10^{11} cm^{-2} and mid 10^{10} eV^{-1}cm^{-2} respectively for both 6H and 4H p-type SiC [1-2]. When utilizing this structure as a MOSFET gate, the two polytypes yield considerably different device characteristics. The 6H-SiC inversion channel mobility approaches 100 cm^2/V-s which is a record high value for thermally grown gate oxides. The 4H-SiC mobility, on the other hand, can be an order of magnitude lower for samples processed side-by-side with the 6H-SiC samples [3]. The additional processing steps needed to fabricate MOSFETs have a greater impact on the 4H-SiC samples, thereby requiring them to be independently optimized. We have found that the thermal budget prior to oxidation is critical when fabricating quality MOS interfaces. The implant activation anneal of the n-type source/drain regions, therefore, is an important factor in the resulting device quality. In this presentation, the temperature and ambient of the anneal are varied to examine their effects on the mobility. In the first experiment, MOSFETs are fabricated on 4H p-type SiC where the only process variable is the anneal temperature performed in Ar. The samples annealed at 1400°C and 1300°C both yield single digit mobility. The 1200°C sample, however, shows promising characteristics with a peak mobility of 25 cm^2/V-s. Decreasing the anneal temperature improves the device characteristics. Using this logic, the best mobility would be attained from samples without any annealing step. Currently, 4H- and 6H-SiC MOSFETs are being fabricated with epitaxial source/drain regions, i.e., without ion implantation and implant activation anneal. The results of this experiment will be presented. SiC power MOSFETs are typically fabricated with p-type implants which require a 1700°C activation anneal [4-5]. At such elevated temperatures, the surface roughens, resulting in very low mobilities (<<1 cm^2/V-s). A possible solution to this problem is silane annealing. Surface morphology studies show that annealing in a silane ambient instead of Ar maintains the integrity of the surface [6]. Two 4H-SiC samples are fabricated into MOSFETs with a 40 min. anneal at 1700°C in silane. One sample has channels formed on an epilayer while the other has implanted channels. Despite the improved surface morphology, the mobility on the epi channel remains in the single digits whereas the implanted channel suffers from fractional mobility. This work is supported by the Office of Naval Research AASERT Grant No. N00014-95-1-1042 and MURI Grant No. N00014-95-1-1302. REFERENCES [1] L.A. Lipkin, et al., Proc. ISCIII-N ?97, Part 2, pp. 853-856, 1998. [2] M.K. Das, et al., J. Electr. Mat., 27 (4), pp. 353-357, 1998. [3] M.K. Das, et al., IEEE Semiconductor Interface Specialists Conference, San Diego, CA 1998. [4] J.N. Shenoy, et al., IEEE Electron Device Letters, 18, pp. 93-95, 1997. [5] J. Tan, et al., IEEE Device Research Conference,

Charlottesville, VA, 1998. [6] M.A. Capano, et al., Electr. Materials Conference, Charlottesville, VA, 1998.

2:30 PM
Electrical Characteristics of Schottky Barriers on 4H-SiC: The Effects of Barrier Height Nonuniformity: *B. J. Skromme*[1]; E. Luckowski[1]; K. Moore[1]; M. Bhatnagar[1]; C. E. Weitzel[1]; T. Gehoski[1]; D. Ganser[1]; [1]Motorola, Inc., Mats. Technology Laboratories, EL720, 2100 E. Elliot Rd. 99164-2814, Tempe, AZ 85284 USA

Schottky barrier diodes are a key component of many SiC devices, such as MESFET's, high-voltage rectifiers, and static induction transistors. Their properties on the 4H polytype are of particular interest, because of its higher and more isotropic mobility compared to 6H, which yields higher current capabilities at a given breakdown voltage. Excellent rectifying characteristics have been reported for 4H-SiC diodes, but in most cases only the properties of "typical" or a few devices have been described with little discussion of diode-to-diode or wafer-to-wafer variations. We will describe the results of an extensive investigation of Schottky diodes using Ti, Ti/Al, Ti/Au, Ni/Au, Ni/Al, and Pt/Au metalization schemes on commercially purchased 4H-SiC epitaxial wafers. Over ten wafers and hundreds of devices were processed and characterized. The material structure was either n⁻ (10^{16} cm⁻³)/n⁺ or n (10^{17} cm⁻³)/n⁺, the latter do ping level being typical of that used in MESFET structures. Post-metalization anneals were performed in nitrogen at temperatures from 150 to 600°C. Both forward and reverse current-voltage (I-V) characteristics were measured along with capacitance-voltage (C-V) properties, primarily at room-temperature. A key finding is the existence of substantial variations in barrier height and ideality factor determined from I-V measurements from diode to diode for each metalization, whereas the barrier heights determined from C-V data were essentially constant. The barrier height determined from I-V measurements is plotted as a function of ideality factor and shows a linear decrease with increasing ideality, with slopes from -0.35 to -0.80 eV. Ideality factors range from 1.03 to 2-3 or higher. We attribute the reduction in effective I-V barrier height (by as much as 0.5 eV) and increased ideality factor to microscopic-scale variations in Schottky barrier height within the contacts, as previously discussed in the case of Si and GaN by Schmitsdorf et al. (J. Vac. Sci. Technol. B 15, 1221 (1997)). The theory of current transport in inhomogeneous Schottky barriers by R. Tung (Phys. Rev. B 45, 13509 (1992)), including the pinch-off effect, is applied to model the data. Extrapolations of the I-V barrier height data to near-unity ideality factors is shown to yield values generally in good agreement with barrier heights determined by C-V measurements, which are relatively insensitive to low barrier height "patches." "Excess" currents are observed at low forward bias in many diodes, and show behavior explainable by the inhomogeneous transport theory of Tung, but not by generation-recombination processes in many cases. The relation of these excess forward currents to reverse-bias leakage will be discussed. *Permanent address: Dept. of Elect. Eng. and Center for Solid State Electronics Research, Arizona State University, Tempe, AZ 85287-5706.

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Characteristics of Nickel Schottky Junctions on Trench Sidewalls of Reactive Ion Etched 4H-SiC Surfaces: *V. Khemka*[1]; T. P. Chow[1]; R. J. Gutmann[1]; [1]Rensselaer Polytechnic Institute, Center for Integrated Electr. and Elect. Manuf., Troy, NY 12180-3590

Reactive ion etching (RIE) is an important part of SiC device fabrication technology because a large percentage of vertical SiC devices, at present, are fabricated using epitaxial capability of experimental devices. Vertical power devices, such as the static induction transitor (SIT), are fabricated with trench gates and any undesirable charactericstic of the contact on trench sidewall and/or bottom (metal-semiconductor junctions) will manifest itself in poor performance. Previously, we have reported the effect of RIE in flourinated plasmas on the performance of planar Ni/4H-SiC Schottky diodes [1]. In this paper, we will present the evaluation of Schottky contacts on the bottom and sidewall surfaces of deep trenches (1.5-2mm)etched in 4H-SiC. The trenches were formed using florinated plasmas (CHF_3/O_2 and SF_6/O_2) with etch rates as high as 85 nm/min using Al and/or Ni transfer masks. The lateral width of the trench was varied from 1.5mm. The sidewalls and bottoms of these trenches are examined using optical microscopy as well as scanning electron microscopy (SEM) for any possible metal-micromasking. Three different kinds of Ni Schottky diodes were prepared. The first was on planar unetched surfaces to serve as control devices, another on planar surfaces subjected to RIE and the last nonplanar one was formed by metal deposition on the RIE-etched trenches. Control diodes indicated excellent forward characteristics with an ideality factor of ~1 and a barrier height of 1.55 eV. Analysis of forward characteristics of planar diodes on etched surface and trenched diodes indicated significant degradation in the electrical characteristics. Ideality factor and barrier height of 2 and 0.93 eV were extracted on planar etched diodes, which are similar to our previously reported results [1]. The characteristics of the Schottky contact on the trench sidewalls were obtained after eliminating the contribution from the Schottky contacts on trench bottom and top of the mesa region. The barrier height on the trench sidewall was thus estimated to be 0.70 eV, more than a factor of two lower than the enetched planar diode. The corresponding ideality factor was 2.3. Reverse saturation current density (J_8) was also found to be significantly higher on the trench sidewall (1.8_10^{-5} A/cm²) than on trench bottom (3.4_10^{-9} A/cm⁻²). Planar diodes with surfaces etched in SF6/O2 showed better forward characteristics than those with surfaces etched in CHF3/O2. The barrier height on the diodes with surfaces etched in SF6/O2 was 1.29 eV with a corresponding ideality factor of 1.26. Reverse characteristics of the devices were measured up to 200°C. Measurements indicated that diodes etched in CHF3/O2 have better leakage current than diodes with SF6/O2 etched surfaces. Reverse leakage currents of the trench devices were measured to be quite high indicating significant contribution from the trench sidewalls. Electric field crowding at the trench corners is also expected to enhance the leakage current by increasing the image force-induced barrier lowering. A more detailed analysis of the forward and reverse characteristics as a function of trench width and mesa width will be presented at the time of the conference. This study demonstrates the RIE-induced damage on the trench bottom and sidewalls on Ni/4H-SiC can have significant impact on SiC power devices such as SIT/MESFET, where Schottky contacts are utilized as basic building blocks. The authors would like to acknowledge the support of this work by Philips, MURI of the Office of Naval Research, and NSF Center for Power Electronics Systems (EEC-9731677). [1]. V.Khemka, T.P. Chow, and R.J. Gutmann, "Effect of reactive ion etched induced damage on the performance of Ni/4H-SiC Schottky diodes", J. Electron. Mats., October 1998.

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High Rate Etching of Silicon Carbide: *F. Khan*[1]; L. Zhou[1]; A. T. Ping[1]; I. Adesida[1]; [1]University of Illinois at Urbana-Champaign, Dept. of Elect. and Comp. Eng., 208 N. Wright St., Urbana, IL 61801-2355 USA

Silicon Carbide (SiC) is a wide bandgap semiconductor that is being investigated intensively for high power, high temperature device applications. 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 100 µm. Etching of SiC is difficult in general. Wet etching is only achieved in an electrochemical cell while conventional reactive ion etching produces very small etch rate. In this paper, we report our work on the investigation of inductively-coupled-plasma reactive ion etching (ICP-RIE) of SiC in SF6-based plasmas. The etch rates of SiC were exhaustively investigated as functions of ICP power, sample bias voltage, pressure, and gas flow rate. Gas mixtures to be investigated include SF6, SF6/Ar,

and SF6/O2. We have obtained etch rates ranging from a few nanometers per minute, which can be used be applied to surface sensitive devices, to ~ 1 μm/min for via-hole process in SF6 plasma. Etch profiles and surface smoothness obtained under these conditions will be characterized with scanning electron microscope (SEM) and atomic force microscopy (AFM). Also, the electrical characteristics of SiC etched at low self-bias will be presented.

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Fast, Smooth, and Anisotropic Etching of SiC using SF6/Ar:
Myeong S. So[1]; Seung-Gu Lim[1]; Thomas N. Jackson[1]; [1]The Pennsylvania State University, Dept. of Elect. Eng., 121 Elect. Eng. East, University Park, PA 16802 USA

Using mixtures of sulfur hexafluoride and argon we have etched SiC at rates as large as 1900 A/min with smooth surfaces and good etch anisotropy. Such etching is useful for SiC vertical UMOSFETs and other device structures. We have investigated magnetically enhanced reactive ion etching of SiC in mixtures of sulfur hexafluoride (SF6) with oxygen (O2) or argon (Ar). Etching using SF6/O2 resulted in roughened surfaces (typically 25 A rms after etching) with a maximum etch rate of about 800 A/min. Etching using SF6/Ar gave smoother surfaces and larger etch rates, most likely because physical sputtering by Ar+ ions helps to remove nonvolatile or low-volatility fluorocarbon or carbon-rich etch products. For example, etching using equal flow rates of SF6 and Ar (each 40 sccm) with a 10 mTorr total pressure and a RF power input of about 2.5 W/cm2 gave an etch rate of nearly 1000 A/min. Atomic force microscopy showed that the surface roughness of SiC etched under these conditions actually decreased slightly (from 6.1 A to 4.4 A rms) and scanning electron microscopy showed good etch anisotropy with slight trenching at feature edges. The etch rate increased to 1900 A/min for a RF power input of about 3.5 W/cm2 with only slightly increased surface roughness. The large etch rate, smooth surfaces, and good etch anisotropy make SF6/Ar etching attractive for SiC device fabrication.

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Analysis of the Temperature Dependence of the SiO_2 / SiC Barrier Height: *Richard Waters*[1]; Bart Van Zeghbroeck[1]; [1]University of Colorado, Dept. of Elect. and Comp. Eng., Boulder 80309-0525 CO USA

A more complete understanding of the Fowler-Nordheim (F-N) tunneling phenomena through thermally grown silicon dioxide (SiO_2) on silicon carbide (SiC) is required if high temperature SiC MOS-based devices are to be realized. Previous studies have shown that the SiO_2/ SiC barrier height is quite sensitive to the applied temperature 1-2. In this paper, we analyze the temperature dependent behavior of F-N tunneling currents through SiO_2 grown on n-type SiC substrates including temperature dependence of the flatband voltage when performing a F-N analysis. The MOS capacitors used in this study were fabricated on n-type 4H and 6H-SiC substrates with doping densities of 10^{17} cm^{-3} as measured from capacitance voltage measurements. In order to insure a clean interface between the SiO_2 and SiC, the samples were RCA cleaned followed by the growth of a sacrificial oxide that was subsequently etched off in HF. The tunnel oxides were then grown in a pyrogenic water vapor atmosphere at 1100°C for 10 min resulting in oxides of 84 Å and 93 Å for the 6H and 4H samples respectively. Thin tunnel oxides were grown in order to limit the effect of surface states on the flatband voltage. The thickness of the oxides was measured by ellipsometry and capacitance-voltage (C-V) measurements. Nickel gate electrodes were then thermally evaporated completing the fabrication process. Room-temperature flatband voltages of 0.9 V and 1.5 V for the 6H and 4H-SiC MOS capacitors respectively were obtained from C-V data. The current voltage characteristics were measured at 20 different temperatures ranging from 27°C up to 300°C. The temperature dependent barrier height was found by performing a Fowler-Nordheim analysis on the data at each temperature. The temperature dependent flatband voltage must be included in order to obtain the correct field across the oxide necessary for the F-N analysis. It was assumed that the change in flatband voltage, as a function of temperature, was due only to a variation in Fermi energy in the SiC and that the interfacial charge remained constant with temperature. An oxide effective mass of 0.42 m$_o$ was used in all F-N calculations. The result of the F-N analysis indicates a linear decrease in barrier height as a function of temperature for both the 4H and 6H samples. The decrease in barrier can be modeled as an effective barrier variation of 2.4 mV/°C and 2 mV/°C for the 4H and 6H-SiC samples respectively. The extracted room-temperature effective barrier heights were found to be 2.18 and 2 eV for the 6H and 4H samples respectively while the extracted barrier heights at 300°C were 1.4 and 1.1 eV for the 6H and 4H-SiC respectively. The barrier heights extracted are smaller than previously reported values due to the inclusion of the flatband voltage in our analysis 1,2. The cause of the temperature dependent barrier lowering and the effect of interfacial charge will be discussed. 1 A. Agarwal, S. Seshadri, L. Rowland, IEEE Elec. Dev. Lett., 18, 592, (1997). 2 E. Bano, T. Ouisse, P. Lassagne, T. Billon, C. Jaussaud, SiC and related materials Conf., Kyoto Jpn., 733, (1995).

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Atomic-Scale Mechanisms of Oxygen Precipitation and Thin-Film Oxidation of SiC: *Massimiliano Di Ventra*[1]; Sokrates T. Pantelides[1]; [1]Vanderbilt University, Phys. and Astron., Stevenson Center, Nashville, TN 37235 USA

The behavior of oxygen in SiC and the mechanisms of SiC oxidation are important issues whose understanding would impact the development of SiC MOSFETS for power electronics. We report first-principles calculations of the atomic-scale dynamics of the nucleation and growth of SiO2 precipitates in SiC and relate the results to thin film oxidation of SiC. The nucleation proceeds via the mutual attraction of two oxygen atoms in two adjacent Si-O-C bridge configurations in the (110) plane of the SiC matrix. A third oxygen atom can bind to the complex in an adjacent Si-O-C bridge, but the resulting structure is metastable. Energy is lowered if the third oxygen atom binds to a C atom and the two are released as interstitial CO. The overall process is exothermic with a reaction energy of about 0.7 eV. The CO molecule diffuses along the [110] tubular directions with the oxygen atom always moving between one Si and two C atoms in different but adjacent sites and the carbon atom "wagging" behind as a C interstitial. The barrier for the diffusion of the CO molecule has been estimated to be about 1.6 eV. The metastable three-oxygen defect is reminiscent of the thermal donor in Si. The three oxygens bind by about 0.5 eV and the defect induces a donor state at about 0.2 eV from the conduction band continuum. Due to its binding energy the defect would rapidly transform to the stable defect responsible for the emission of a carbon interstitial suggesting that oxygen complexes in SiC cubic phase are unlikely. The above results on SiO2 precipitation bear relevance to SiC oxidation. As oxygen atoms arrive at the advancing SiC/SiO2 interface, the process described above results in the emission of CO molecules, in agreement with observations. In contrast to the case of Si oxidation, thermal-donor-like defects are unlikely to form at the SiC/SiO2 interface. This work was supported in part by a DARPA grant N. MDA972-98-1-0007 and EPRI grant N. W08069-05.

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Session T. Materials Integration: Growth and Characterization

Thursday PM Room: State Street
July 1, 1999 Location: University Center

Session Chairs: Theresa Mayer, Penn State University, University Park, PA USA; Matt Seaford, Air Force Research Laboratory, WPAFB, OH USA

1:30 PM
Lattice-Mismatched InGaAs Layers Grown on GaAs and InP Compliant Substrates: *Koen Vanhollebeke*[1]; Ingrid Moerman[1]; Peter Van Daele[1]; Piet Demeester[1]; [1]University of Gent-IMEC, Dept. of

Info. Tech. (INTEC), Sint-Pietersnieuwstraat 41, Gent, - 9000 Belgium

Thin GaAs compliant substrates have been developed in order to reduce the strain in lattice-mismatched layers during epitaxial overgrowth. The GaAs compliant substrates are fabricated by bonding a GaAs substrate, containing an AlGaAs etch stop layer and a thin (30-80 Å) GaAs layer, on a host GaAs substrate. Compliant substrates with twist angles from 10 to 45° were made. The layers are deposited by low pressure organo-metallic vapor phase epitaxy (OMVPE). Several AlGaAs etch stop layers, which differ in composition (50-70% Al) and thickness (200nm - 1μm), were investigated. The wafer bonding was performed in a nitrogen atmosphere, and the optimized temperature and duration are respectively 660°C and one hour. Using the appropriate substrate cleaning before bonding (and overgrowth), the resulting compliant substrates have, after mechanical and chemical thinning, mirror-like surfaces. The GaAs compliant substrates are overgrown with InGaAs quantum wells and bulk layers. Normarski phase contrast microscopy, room-temperature photoluminescence (PL) and double crystal X-ray diffraction (DXRD) are used to characterize the hetero-epitaxial layers. The surface quality of the compliant substrates was investigated by the OMVPE growth of In$_{20}$GaAs/GaAs quantum wells. The intensity of the room-temperature PL at 980nm was comparable with the GaAs reference. Up to 2.2% lattice-mismatched and 600 nm thick InGaAs layers were grown on the 60 Å thick compliant substrates. This results in smooth and cross-hatch free surface morphology for an InGaAs layer thickness exceeding to 50 times the Matthews-Blakeslee (MB) critical thickness on 60 Å thick compliant substrates. (004) and (115) DXRD measurements on the previous substrates show a reduced peakwidth of the heteroepitaxial layer and indicate a significant increase in relieved strain of that layer. Furthermore an investigation of the OMVPE growth conditions on the GaAs compliant substrates, especially for the growth rate and temperature, was done. The goal of this research is the application of the compliant substrates for the fabrication of extended wavelength InGaAs-detectors for detection up to 2.5 μm. Because the thickness and/or lattice-mismatch of an epilayer overgrown on a compliant substrate is limited, research is underway to extend the concept and technique of compliant substrates to InP and other materials. An InP (40-60 Å) compliant substrate was developed using an 400nm thick lattice- matched InGaAs etch stop layer and bonded under nitrogen around 570°C. The resulting compliant substrates have also mirror-like surfaces. Preliminary growth experiments on InP compliant substrates however show a less significant 'compliant' effect, e.g. the surface roughness of the 200nm In$_{75}$GaAs layer is comparable with the InP reference substrate. Further research is underway to optimize the bonding parameters, in order to reduce the bonding strength, which is likely to increase the 'compliance' effect in the case of InP. This work was supported by the ESA/ESTEC (CCN3 to contract 11141/94/NL/CN).

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A Comparison of Experimental and Calculated HRXD Spectra of Mismatched InGaAs Films Grown on Borosilicate Glass-Bonded GaAs Compliant Substrate Structures: *P. D. Moran*[1]; D. M. Hansen[1]; J. G. Cederberg[1]; K. A. Dunn[1]; L. J. Mawst[1]; S. E. Babcock[1]; R. J. Matyi[1]; T. F. Kuech[1]; [1]University of Wisconsin, 1415 Johnson Dr., Madison, WI 53706 USA

The ability of compliant substrates to modify the relaxation behavior of subsequently grown mismatched films has been demonstrated. The compliant substrates consisted of 10nm thick GaAs growth template bonded to a CVD-borosilicate glass layer on a handle wafer by applying 1-10MPa of pressure at 550°C. The breadth of high resolution x-ray diffraction (HRXD) peaks from 3 μm thick highly mismatched (3%) In0.40Ga0.60As films grown on these substrates is significantly narrower than for films grown simultaneously on conventional substrates, indicating an improvement in structural quality. The position of the HRXD peak from 3 μm of slightly mismatched (0.1%) In0.01Ga0.99As films grown on compliant substrates differs from that of the film simultaneously grown on the conventional substrate, indicating an enhancement of relaxation due to growth on the compliant substrates. The breadth of the HRXD peaks from the slightly mismatched InGaAs grown on the compliant substrates were similar to that from the film grown on the conventional substrate, indicating little or

no structural degradation during enhanced relaxation. The efficacy of the compliant substrate will depend upon the nature of the template-to-glass layer bond and the growth conditions employed. In this work we compare the measured HRXD results to the calculated HRXD spectrum for growth on an ideal compliant substrate free of structural defects and unconstrained in the plane of the template/film interface. The peak breadths and positions observed in the slightly mismatched films are similar to that which would be calculated for growth on an ideal compliant substrate. The peak breadths observed from the highly mismatched InGaAs films are significantly broader than the calculated values. These results are interpreted in terms of bonding-induced structural defects in the compliant substrate and the limits imposed on the compliant substrate's efficacy by the nature of the template/handle bond in conjunction with the growth conditions employed.

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Strain Relaxation in InxGa1-xAs Lattice Engineered Substrates: *Prashant M. Chavarkar*[1]; Lijie Zhao[2]; Stacia Keller[1]; Andrew Fisher[3]; James S. Speck[2]; Umesh K. Mishra[1]; [1]University of California, Dept. of Elec. and Comp. Eng., Santa Barbara, CA 93106 USA; [2]University of California, Mats. Dept., Santa Barbara, CA 93106 USA; [3]University of California, QUEST, Santa Barbara, CA 93106 USA

We demonstrate an approach to fabricate quasi-substrates of arbitrary lattice constants. This utilizes the process of relaxation of a coherent hypercritical thickness (h > hcritical) strained semiconductor over-layer (InxGa1-xAs) in direct contact with an oxidizing Al-containing semiconductor (i.e. AlAs or AlGaAs). The process of strain relaxation is studied by varying the strain in the as-grown InxGa1-xAs template and by varying the nature of the InxGa1-xAs/oxide interface. Changing the Indium composition in the template varies the strain in the template and the initial misfit dislocation density. Varying the oxidation temperature controls the nature of the InxGa1-xAs/oxide interface. The epitaxial structures investigated in this study consisted of strained InxGa1-xAs template layers grown on AlAs oxidation layer on a GaAs substrate. The indium compositions investigated were 20 %, 30 % and 40 %. The thickness of the InxGa1-xAs template layers was 20 times the Matthews-Blakslee critical thickness for each composition. The InxGa1-xAs template layers were grown by molecular beam epitaxy at low temperature (400-430°C) to minimize the formation of threading dislocations and maintain a two-dimensional growth front. The as grown InGaAs templates show a smooth surface morphology with a rms roughness less than 10 Å and low threading dislocation density as evidenced from Cross sectional TEM micrographs. After growth the substrate was patterned using photolithography and reactive ion etching into 100 μm x 100 μm square mesas to enable lateral oxidation of the AlAs layers. The degree of strain relaxation was determined by X-Ray diffraction of as-grown and oxidized templates. Off-axis (115 and -1-15) X-ray diffraction scans were used to determine the in-plane and out-of-plane lattice constants. Self-consistency of the measurements was checked by on-axis (004) X-ray diffraction which was used to determine out-of-plane lattice constant independently. The strain is InxGa1-xAs templates was reduced after oxidation as observed from increased strain relaxation. X-Ray diffraction measurements of thermally annealed InGaAs templates under the same conditions revealed no strain relaxation. This indicates that enhanced strain relaxation is not due to increased thermal energy but is caused by the process of oxidation at the InGaAs/AlAs interface. The degree of strain relaxation in InxGa1-xAs templates was found to increase with oxidation temperature, whereas the efficiency of strain relaxation of found to decrease with the Indium composition. For an In0.2Ga0.8As template the strain relaxation can be increased from 35% for an as-grown template to 90% for a template oxidized at 450°C. However in the case of an In0.4Ga0.6As template the degree of strain relaxation changes from 57% for an as-grown template to 70% for a template oxidized at 450°C. It is proposed that the enhanced strain relaxation is due to enhanced movement of threading dislocation due to stresses ge nerated during the lateral oxidation process. Also the porous InxGa1-xAs/Al2O3 interface minimizes the interaction of threading dislocations with existing misfit dislocation segments, a mechanism which limits strain relaxation in conventional approaches like direct growth. The reactive removal of misfit dislocation cores during the process of oxidation further reduces barriers to threading dislocation motion. Increased oxi-

dation temperatures result in a more porous interface and enhanced removal of misfit dislocation cores and therefore increase the degree of strain relaxation. On the other hand, the misfit dislocation density increases with Indium composition and reduces the efficiency of strain relaxation by increasing the barriers to threading dislocation motion. The relaxed InGaAs layers can be used as quasi-substrates (Lattice Engineered Substrates) for growth of material systems with lattice constants between the commercially available binary III-V substrates. This work was supported by AFOSR under the PRET program.

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On the Strain Relaxation and Misfit Dislocation Introduction Mechanisms in Highly Lattice Mismatched InAs/GaP Epitaxy:

Vidyut Gopal[1]; Alexander L. Vasiliev[1]; Enhsing Chen[2]; Eric P. Kvam[1]; Jerry M. Woodall[2]; [1]Purdue University, School of Mats. Eng., 1289, MSEE Bldg., W. Lafayette, IN 47907 USA; [2]Yale University, Dept. of Elect. Eng., 15, Prospect St., P.O. Box 208284, New Haven, CT 06520-8284 USA

Strain relaxation in epitaxial layers grown on lattice mismatched substrates is a topic that has attracted considerable attention. Most research has concentrated on low lattice mismatch regimes (<2%). In such systems, interfacial misfit dislocations (MD) are usually formed by one or both of the following mechanisms. First, they can be nucleated at the surface of the growing layer, and glide down and along {111} planes onto the interfacial plane, where they relax strain. They can also form as a result of inclined threading dislocations bending over at the interface as a result of the mismatch strain. Consequently, the MDs are of (60 degrees) mixed character. Comparatively little effort has been devoted to the study of high lattice mismatched epitaxy. These microstructures have been found to consist mainly of 90 degrees sessile MDs and in-situ Transmission Electron Microscopy (TEM) studies of Ge films growing on Si (mismatch ~ 4%) indicate that these dislocations are directly introduced at the edge of growing is lands during the early stages of growth (1). We have investigated the growth of InAs on GaP by Molecular Beam Epitaxy (MBE), with a mismatch of ~ 11%, the largest among the III-arsenides and the III-phosphides. A perfect epitaxial relationship is maintained between the film and substrate and strain is relaxed by a periodic, two dimensional network of 90 degrees MDs spaced ~ 4 nm apart. However, for the first time, we report that the strain relaxation proceeds by two distinct dislocation introduction mechanisms. In the very early stages of growth, the majority of the MDs are directly introduced, most probably at the edge of the growing InAs islands. As growth proceeds, the islands coalesce and the direct introduction mechanism becomes energetically unfavorable. MD introduction then continues by a cooperative surface nucleation mechanism (2) of 60 degrees dislocations, which glide to the interface and combine to form 90 degrees MD segments. Such a two stage mechanism has a pronounced influence on the MD microstructure and the resulting threading dislocation density. The possibility that variable amounts of strain can be retained in thin InAs layers gives additional flexibility in device design. The fact that most of the MDs are introduced directly at the interface means that the cross-hatch problem that leads to roughening of surfaces and interfaces is avoided in this system. Thus, it will be shown that an extremely high mismatch system could be more suitable for device design than some lower mismatch systems. (1) F.K. LeGoues, J. Tersoff, M.C. Reuter, M. Hammar and R. Tromp, Appl. Phys. Lett. Vol 67, 2317 (1995). (2) E.P. Kvam, D.M. Maher and C.J. Humphreys, J. Mater. Res. Vol 5, 1900 (1990).

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Epitaxial Growth and UV Luminescence of CaF2/ZnO/CaF2 Heterostructures on Si(111):

Dr. Masahiro Watanabe[1]; [1]Tokyo Institute of Technology, Research Center for Quantum Effect Electronics, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552 Japan

We have demonstrated epitaxial growth and room temperature ultraviolet (UV) emission of epitaxial zinc oxide (ZnO) grown on a single-crystalline CaF_2 layer on Si(111) substrate. Highly c-axis oriented ZnO was grown on $CaF_2(111)$ layer using RF sputtering followed by annealing in ultra-high vacuum and over growth of CaF_2 using molecular beam epitaxy (MBE). UV photoluminescence (PL) and electroluminescence (EL) was observed at room temperature and the maxi-

mum peak wavelength corresponded to the band gap energy (E_g) of ZnO. Zinc oxide (ZnO) is an attractive candidate for ultraviolet emitting material for its direct band gap energy (E_g) of 3.3 eV at room temperature. ZnO has wurtzite lattice structure and has strong tendency for crystal self-organization even on the materials with different crystal structure and lattice constant. We have studied the formation technique of epitaxial ZnO on silicon substrate using nanometer-thick CaF_2 interlayer, which will act as energy barriers for tunneling carrier injection of EL devices. Fluorite (CaF_2) is a well-known material for epitaxial growth on silicon (Si) substrate using Molecular Beam Epitaxy (MBE) based technique. CaF_2 has fluorite lattice structure that is well matched to the lattice structure of Si with mismatches of +0.6% at room temperature. CaF_2 layer with 10 nm in thickness was formed on Si(111) substrate using MBE with slightly ionized CaF_2 ion beam at substrate temperature of 700°C. This yielded flat CaF2(111) surface with fluctuation of approximately 1 nm. On the CaF_2(111), ZnO layer was formed using RF sputtering with 100% O2 plasma and with ZnO target. Subsequently, 10 nm-thick CaF_2 layer was grown over ZnO layer at 450°C followed by annealing at 700°C for 60 min in ultra-high vacuum (UHV) chamber. After the annealing in UHV, single-crystalline CaF_2/ZnO/CaF_2 heterostructure was obtained and abrupt heterointerface was confirmed by the cross sectional lattice image of transmission electron microscopy (TEM). C-axis oriented ZnO was observed between the CaF_2(111) layers and eight ZnO unit cells aligned to seven CaF_2 unit cells, which almost agrees with mismatches of 11% between CaF_2(111) and ZnO(0001) at room temperature. Device structures for carrier injection was fabricated using CaF_2/ZnO/CaF_2 heterostructures grown on p-type Si(111) substrate. Contact holes through SiO_2 insulation layer were formed using photolithography and RIE dry etching. 100 nm-thick ITO transparent electrode was used for electron emitter as well as contact pad. EL measurement was carried out at room temperature with pulse (1:1) injection and band edge emission of ZnO at around 390 nm was observed in EL spectra. Growth condition dependence of PL and EL spectra will be also discussed. This work was supported by The Japan Society for the Promotion of Science (JSPS-RFTF 96P00101), and by the Research Center for Ultra-High-Speed Electronics.

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Comparison of InGaSb/InAs Superlattice Structures Grown by MBE on GaSb, GaAs, and Compliant GaAs Substrates:

D. H. Tomich[1]; K. G. Eyink[1]; G. L. Brown[1]; L. Grazulis[1]; K. Mahalingam[1]; M. L. Seaford[1]; C. H. Kuo[2]; W-Y. Hwang[2]; C. H. Lin[2]; [1]Air Force Research Laboratory, Mats. and Manuf. Directorate, 3005 P St. Suite 6, WPAFB, OH 45433-7707; [2]Applied Optoelectronics Inc., Sugar Land, TX 77478

This paper contains the characterization results for indium arsenide/indium gallium antimonide (InAs/InGaSb) superlattices (SL) that were grown by molecular beam epitaxy (MBE) on standard gallium arsenide (GaAs), standard GaSb, and compliant GaAs substrates. The atomic force microscopy (AFM) images, peak to valley measurement, and surface roughness measurements are reported for each sample. The high resolution x-ray diffraction (HRXRD) analysis found different 0th order SL peak to GaSb peak spacings for the structures grown on the different substrates. These peak separations are consistent with different residual strain states within the SL structures. The cutoff wavelength for the SL structure on the compliant GaAs, control GaSb, and control GaAs was 13.9um, 11um, and no response, respectively.

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Low Dislocation Relaxed SiGe Grown on a Novel Compliant Substrate:

Yuhao Luo[1]; Jian-Lin Liu[1]; Gaolong Jin[1]; Kang L. Wang[1]; Chih Chen[2]; King-Ning Tu[2]; Caroline D. Moore[2]; Mark S. Goorsky[2]; [1]University of California at Los Angeles, Dept. of Elect. Eng., Eng. IV 17-142, 405 Hilgard Ave., Los Angeles, CA 90095-1594 USA; [2]UCLA, Dept. of Mats. Sci. and Eng., 6532 Boelter Hall, 405 Hilgard Ave., Los Angeles, CA 90095-1595 USA

Recently, compliant substrate has attracted lots of interest in the lattice-mismatched epitaxy. In this paper, a novel compliant substrate was successfully fabricated for growth of high quality relaxed SiGe epitaxial layer. The compliant substrate was accomplished by first forming

a high B_2O_3 concentration borosilicate glass in the SOI wafers through boron and oxygen implantation followed by a high temperature annealing, and then by thinning down the top Si layer with thermal oxidation and HF dip. The average roughness of the substrate surfaces was measured with AFM to be about 5 Å. Compliant substrates, with 5% and 20% B_2O_3, respectively, in the SiO_2 layer of SOI were prepared by the above method, followed by 120 nm thin $Si_{0.75}Ge_{0.25}$ deposition at 500°C. After SiGe deposition, parts of the samples were annealed for 1 hour at 850°C in nitrogen. The samples were characterized by double crystal x-ray diffraction (DXRD) and high resolution transmission electron microscopy (HRTEM) to determine the extent of strain relaxation, the Ge composition, and the dislocation distribution and density. DXRD data give relaxation of 79±10% for 5% BSG sample and 64±3% for 20% BSG sample, with a much higher quality in the latter. From TEM, the dislocation density in the as grown 5% BSG sample is 5 x 10^8 cm^{-2}, which increases to 1.5 x 10^9 cm^{-2} in the annealed sample. However, no misfit and threading dislocations were observed in the SiGe layer by TEM in 20% BSG sample, for both the as grown and the annealed cases of sample B, suggesting dislocation densities are below 10^8 cm^{-2}. Two similar but thicker (500 nm) samples of $Si_{0.75}Ge_{0.25}$ were also grown on the two kinds of substrate. Using defect etching, Normarski micrographs showed that the threading dislocation density in SiGe was below 10^5 cm^{-2} for the sample grown on the 20% BSG compliant substrate, but more than 10^6 cm^{-2} for sample grown on 5% BSG compliant substrate. In conclusion, 20% BSG compliant substrate have been shown to allow SiGe layers to be grown with low dislocation density. The thin Si layer (< 20 nm) on the "soften" borosilicate glass may become strained to accommodate misfit of the grown SiGe and the Si layer during the growth.

4:10 PM

Optically-Pumped Mid-Infrared Lasers on Traditional and Compliant Substrates: *Stefan J. Murry*[1]; Chau-Hong Kuo[1]; Chih-Hsiang Lin[1]; Han Q. Le[1]; Shin-Shem Pei[1]; [1]University of Houston, Space Vacuum Epitaxy Center, SR1 Rm. 724, 4800 Calhoun, Houston, TX 77204-5507 USA

Mid-infrared (IR) lasers have been proposed for use in a variety of applications from military countermeasures to medical diagnostics. Recent progress has shown high power operation of optically pumped lasers employing an active region exploiting the type-II band alignment of the InAs/InGaSb material system. Power output in excess of 1.5 Watts total peak output power under pulsed operation at a substrate temperature of 80 K and 1% duty cycle has been demonstrated for devices grown on GaSb substrates. Currently, one limitation on high power, high temperature operation is poor heat conduction through the substrate, which can be improved greatly by mounting the laser sample with the epitaxial side down (i.e. nearest the heat sink). In order to provide optical transparency, a novel GaAs compliant substrate has been fabricated in our laboratory using wafer fusion techniques. Preliminary data shows good performance for type-II mid-IR optically pumped lasers grown on these compliant substrates by molecular beam epitaxy (MBE). Peak output power near 0.8 W, again under pulsed operation at low temperature, has been measured for lasers grown on these compliant substrates.

4:30 PM

Optically Pumped Stimulated Emission in Freestanding GaN Prepared by Hydride Vapor Phase Epitaxy: *S. T. Kim*[1]; D. C. Moon[2]; C. K. Kim[3]; Y. H. Choi[3]; T. K. Yoo[3]; [1]Taejon National University of Technology, Dept. of Mats. Eng., 305-3 Samsung-dong, Dong-gu, Taejon 300-717 Korea; [2]Kwangwoon University, Dept. of Electr. Mats. Eng., 447-1 Wolgye-dong, Nowon-gu, Seoul 139-701 Korea; [3]LG Corporate Institute of Technology, Optoelectronic Group, 16 Woomyeon-dong, Seocho-gu, Seoul 137-724 Korea

A major limitation of the current technology for GaN-based device technology is the availability of suitable substrates for homoepitaxy. In this paper, we describe the production of freestanding GaN via the hydride vapor phase epitaxy (HVPE) technique and its properties. A HVPE was employed to grow a thick GaN films on (0001) sapphire substrate and the subsequent mechanical removal of the sacrificial substrate resulted in the freestanding GaN substrates without cracks, having a present maximum area of 10 x 10 mm2 and a thickness of 350 ¥

im. X-ray measurements of freestanding GaN indicate excellent crystallinity, with FWHM values less than 300 arcsec. Room-temperature PL measurements of GaN substrate indicate strong near-band-edge emission with FWHM values less than 60 meV and no detectable deep level emission. We also observed the room-temperature optically pumped stimulated emission (SE) from a width of 1 mm cleaved cavity prepared from freestanding GaN. The SE at room-temperature from the cleaved edge of the GaN developed between the near-band-gap edge transition and the shallow donor-acceptor pair recombination. With an increase in the optical pumping-power density, the emission peak was red-shifted by ~2 meV/(MW/cm2), and the full width at half maximum (FWHM) of the peak decreased. At the maximum power density of 2 MW/cm2, the peak energy and the FWHM of the SE were 3.318 eV and 8 meV, respectively. The dependence of the excitation power on the integrated emission intensity indicate a threshold pump power density of Ith = 0.37 MW/cm2 for one set of SE, and output becomes highly TE-polarized. The freestanding and crack-free GaN substrates prepared through this work can be used for homoepitaxial growth of GaN-based optoelectronic devices. Details of the growth and properties of the freestanding GaN substrates will be discussed.

4:50 PM Late News

Session U. Thermophotovoltaic Materials & Devices

Thursday PM   Room: Santa Barbara Harbor
July 1, 1999   Location: University Center

Session Chairs: L. Ralph Dawson, UNM-CHTM, Albuquerque, NM USA; Parvez Uppal, Lockheed Martin, Nashua, NH USA

1:30 PM

Photon Recycling in 0.53 eV InGaAsSb: *Greg Walter Charache*[1]; [1]Lockheed Martin, Knolls Atomic Power Laboratory, River Rd., Schnectady, NY 12065-1072 USA

RF-Photoreflectance lifetime measurements were performed on 0.53 eV InGaAsSb double heterostructures grown lattice-matched on GaSb substrates. Direct evidence of photon recycling has been observed in 0.53 eV InGaAsSb at room-temperature. It is believed this is the lowest bandgap material where photon recycling has been reported. The unpolished back surface of the GaSb substrate was modified to create an absorbing (annealed gold) or reflecting (bare surface / unannealed gold) interface. Fifty percent longer lifetimes were observed with a reflecting interface in comparison to an absorbing interface at room-temperature. These observations have direct implications on the design of thermophotovoltaic energy conversion diodes. Current device designs utilize an alloyed Au-based back contact which will not take full advantage of photon recycling effects. The incorporation of a back surface reflector will increase short circuit current and open circuit voltage due to the utilization of photon recycling and a 2-pass architecture. Initial modeling and experimental results are presented

1:50 PM

Spectral Ellipsometry of GaSb and GaInAsSb/GaSb: Experiment and Modelling: *Martin Munoz*[1]; K. Wei[1]; Fred H. Pollak[1]; Greg Charache[2]; C. A. Wang[3]; [1]Brooklyn College of CUNY, Phys. Dept, 3438N, 2900 Bedford Ave., Brooklyn, NY 11210 USA; [2]Lockheed Martin, Schenectady, NY 12301 USA; [3]MIT Lincoln Laboratory, Lexington, MA 02420 USA

Spectral ellipsometry at 300 K, in the range 0.3–5.4 eV, has been used to determine the complex optical constant ÿ(E) [= ÿ1+iÿ2] of bulk GaSb and an epilayer of GaInAsSb/GaSb (001) fabricated by OMVPE. These materials are significant for thermal photovoltaic (TPV) appli-

cations. The native oxide was removed by a chemical etching procedure and the measurements were performed in a nitrogen atmosphere to prevent subsequent oxide formation. We have fit the data (after oxide removal) over the entire spectral range using the Holden formalism [1], a comprehensive model dielectric function based on the energy-band structure near critical points (CPs) plus discrete and continuum excitonic effects at the $E0$, $E0+\ddot{y}0$, $E1$, and $E1+\ddot{y}1$ CPs. The ability to fit the data using analytical expressions is very useful for modeling TPV device parameters. In addition to the energies of these band-to-band CPs, our analysis also yields information about the binding energies of not only the 3D exciton associated with $E0$ (R0) but also the 2D exciton related to the $E1$, $E1+\ddot{y}1$ CPs (R1). We find that $E0 = 0.725$ eV and 0.47 eV for GaSb and GaInAsSb, respectively. Comparison of the obtained $R1 = 30$ meV for GaSb with values for a number of other zincblende-type materials, i.e., ZnCdSe/InP, CdTe, CdS, and In0.66Ga0.34As, indicates that R1 is in good agreement with effective mass and theories, i.e., $>>$. The ability to evaluate R1 has ramifications for recent first-principles band structure calculations which have included exciton effects at both $E0$ and $E1$ [2].

2:10 PM

Phase Instabilities and Microstructure in InGaAsSb/GaSb Heterostructures: Y-C Chen[1]; V. Bucklen[1]; *Krishna Rajan*[1]; C. Wang[2]; G. Nichols[3]; P. Sander[3]; G. Charache[3]; [1]Rensselaer Polytechnic Institute, Mats. Sci. and Eng. Dept, Bldg. MRC-110, Troy, NY 12180-3590 USA; [2]Lincoln Laboratories, Lexington, MA 02420-1072 USA; [3]Lockheed-Martin Corporation, Schenectady, NY 12301-1072 USA

It is well known that miscibility gaps exist within the bulk quaternary InGaAsSb alloy system. In this paper we explore the relationship between theoretically predicted limits of phase stability in bulk materials and the experimental observations of phase instabilities in epitaxial systems. We explore the different microstructural length scales of phase instabilities observed in this quaternary system and the processing parameters that appear to control these changes. Using transmission electron microscopy and X-ray diffraction, well outline the different types of phase transformations that occur in epitaxial InGaAsSb films grown by metalorganic chemical vapor deposition (MOCVD) on (100) GaSb. These include spinodal decomposition, short-range ordering, long-range ordering, and very long period compositional modulations. The crystallographic dependence of these phase instabilities has been documented. Correlations of diffraction-based observations to photoluminescence and mobility data are presented.

2:30 PM

OMVPE Growth of InGaAsSb Thermophotovoltaic Cells: N. A. Morris[1]; *Z. A. Shellenbarger*[2]; D. Z. Garbuzov[1]; R. U. Martinelli[1]; V. B. Khalfin[1]; H. Lee[1]; G. C. Taylor[1]; G. S. Tompa[2]; J. C. Connolly[1]; [1]Sarnoff Corporation, 201 Washington Rd., Princeton, NJ 08543; [2]Structured Materials Industries, Inc., 120 Centennial Ave., Piscataway, NJ 08854

The growth of InGaAsSb thermophotovoltaic (TPV) cells using organometallic vapor-phase epitaxy (OMVPE) is reported. The high throughput, excellent uniformity and reproducibility of OMVPE make it the preferable method for economic production of TPV cells. Growth was conducted in a low-pressure, vertical rotating-disk reactor. Precursors used were trimethylgallium (TMG), trimethylindium (TMI), trimethylantimony (TMSb), and arsine. Doping of the InGaAsSb material was explored using dimethylzinc (DMZ) and carbon tetrachloride (CCl_4) for p-type doping and hydrogen selenide (H_2Se) for n-type doping. The InGaAsSb epitaxial layers were grown lattice-matched to GaSb substrates. The composition of the InGaAsSb material was varied corresponding to bandgap energy of the material in the 0.55 to 0.52 eV range. The material properties of InGaAsSb layers were assessed using X-ray diffraction, photoluminescence and Van der Pauw measurements. Detailed results on the growth process and device properties are presented. Once material growth was established, 1 cm x 1 cm heterostructure TPV cells were fabricated. These TPV device structures consisted of an n-type GaSb buffer layer, n-type InGaAsSb base layer, p-type InGaAsSb emitter layer, and highly doped p-type GaSb cap layer to facilitate ohmic contact to the device. The TPV cells were characterized by quantum efficiency and current-voltage measurements. The electrical characteristics of these cells are presented and compared with similar structures grown by molecular beam epitaxy (MBE).

2:50 PM

A Study of the Relative Tilt of GaInSb Epitaxial Layers on GaSb Substrates Grown by Metalorganic Vapor Phase Epitaxy: *Ishwara B. Bhat*[1]; Hassan Ehsani[1]; Ronald Gutmann[1]; Greg Charache[2]; Mathew Freeman[2]; [1]Rensselaer Polytechnic Institute, ECSE Dept., JEC 6003, 110 8th St., Troy, NY 12180 USA; [2]Lockheed Martin Corporation, Schenectady, NY 12301

In lattice mismatched epitaxial systems, the mismatch is generally accommodated by misfit dislocations. In some systems, a slight tilting of epitaxial layers with respect to the substrates is also common and this "tilting" also accommodates the lattice mismatch. However, to date, layer tilt with respect to the substrate has not been observed when exactly oriented substrates are used for epitaxial growth. We have observed an unexpectedly large relative tilt between Ga0.8In0.2Sb epitaxial layers and GaSb substrates, when exactly (100) oriented GaSb substrates are used for growth. GaInSb epitaxial layers were growth on (100) GaSb substrates by metalorganic vapor phase epitaxy and the relative tilt formed between Ga0.8In0.2Sb epitaxial layers and GaSb substrates were studied using double crystal x-ray diffractometry. These measurements revealed that the tilt angle between the Ga0.8In0.2Sb epitaxial layers and GaSb substrates increases as the layer thickness increases. Transmission electron micrographs of these layers showed that the threading dislocations are pinned and propagate parallel to the growth surface at different distances from the interface. A strong correlation has been established between the variation of the tilt angle and the relaxation of residual strain in the layers. The structural characteristics of these layers as a function of the compositional variation showed that the amount of tilt angle is small when the indium concentration was in the range from 0 to 12%, but increases at higher indium concentrations. GaInSb layers with poor crystalline quality and small tilt angle were obtained when the indium concentration was more than 25%. The tilt angle between the Ga0.8In0.2Sb epitaxial layers and GaSb substrates grown at temperatures ranging from 560 C to 620 C was essentially identical indicating that the tilt formation is not a kinetic effect. This is the first time such a large amount of tilt has been observed when nominally oriented substrates were used for growth.

3:10 PM Break

Session V. Thermoelectric and Other Narrow Gap Materials

Thursday PM   Room: Santa Barbara Harbor 1
July 1, 1999   Location: University Center

Session Chairs: Tim Sands, University of California-Berkeley, MS & ME Dept., Berkeley, CA USA; Kang Wang, University of California, EE Dept., Los Angeles, CA USA

3:30 PM

MOCVD Growth of High Mobility InSb on Si Substrates for Hall Effect Applications: *Michael W. Pelczynski*[1]; Jean J. Heremans[1]; [1]Emcore Corporation, ERA, 394 Elizabeth Ave., Somerset, NJ 08873 USA

Indium antimonide is a promising high mobility material for Hall and magnetoresistive devices, for applications in speed and position sensing in the automotive and consumer electronics industries. Mismatch between the MOCVD-grown InSb epitaxial film and the substrate unavoidably degrades mobility. As a compromise between cost and mismatch, semi-insulating GaAs is typically chosen as the substrate. To lower substrate cost however, in this work we explore the growth of high mobility InSb on 4" high resistivity Si substrates using a thin GaAs buffer layer. GaAs growth conditions studied included buffer/

nucleation layer growth rate, nucleation temperature, layer thickness, pre-deposition, substrate orientation and V/III ratio. X-ray FWHMs as low as 190 sec^{-1} were obtained for thin, @.1 mm films. Our study of Te doped n-InSb films on GaAs/Si of different thicknesses indicates a minimum InSb thickness of @1 mm is required to obtain mobilities necessary for satisfactory magnetic sensitivity. Growth of 1.5 mm n-InSb on GaAs/Si substrates results in specular films featuring mobilities in excess of 38,000 cm²/Vs (RT), with tolerable drops in mobilities at temperatures up to 160°C. SIMS measurements do not observe Si in the InSb epitaxial layer above the detection limit of the instrument (5 x 1016 cm^{-3}), proving the feasibility of dopant control. Thermal cycling between -196°C and 200°C does not affect the film morphology and leads to a small drop in mobility (-3 %), showing that the large discrepancy in thermal expansion coefficient between Si and InSb does not substantially deteriorate the InSb properties. Finally, good uniformity of transport properties over the entire wafer area has been demonstrated.

3:50 PM
The Effect of Annealing Temperature on the Structural and Electrical Properties of Au/n-GaSb Contacts: *H. Ehsani*[1]; C. Hitchcock[1]; R. J. Gutmann[1]; I. Bhat[1]; G. Charache[2]; M. Freeman[2]; [1]Rensselaer Polytechnic Institute, Elect., Comp., and System Eng., Troy, NY 12180 USA; [2]Lockheed Martin Corporation, Schenectady, NY 12301-1072 USA

The structural and electrical properties of deposited Au onto n-GaSb and the correlation between them as a function of annealing temperature have been determined, using x-ray diffraction, I-V measurement, and cross-sectional scanning electron microscopy. In the as-deposited state, the electrical behavior of 0.5mm evaporated Au was Schottky-like. X-ray diffraction measurement did not show any chemical reactions between Au and GaSb. After annealing the contact at 150°C for 90 seconds, both the AuSb2 compound and two phases of Au0.70Ga0.30 (b phase) and Au0.79Ga0.21 (g phase) were formed, while the contact remained Schottky-like. The golden color observed after the deposition of 0.05mm and 0.5mm Au vanished after annealing for 4 seconds and 90 seconds, respectively. Cross-sectional field emission scanning electron microscopy (CSFESEM) showed two distinguish features of compounds, below and above the original Au/GaSb interface. Upon annealing the contact at 300°C for 30 seconds, the GaAu2 compound in addition to AuSb2 compound was observed with ohmic I-V characteristics and a contact resistivity of 2x10^{-6}W -cm². The reaction depth is about 1mm below the interface and about 0.3mm above the interface, as determined by CSFESEM. As the annealing temperature increased from 300°C to 400°C, the AuGa compound formed, in addition to the GaAu2 and AuSb2, and the contact resistivity was increased. The contact depth also increased and the surface morphology became rough. Phase transformation did not occur as the annealing time varied from 0.5 to 20 minutes. At all annealing temperatures, no change in the Au-Sb reaction was observed, indicating that the reactions between Au and Ga are responsible for the changes in contact resistivity of Au/n-GaSb. With 500°C annealing for 30 seconds, the surface morphology became extremely rough and the Au-based compounds were not observed.

4:10 PM
300K Thermoelectric Figure of Merit in the Range of 3 Utilizing Phonon-Blocking Electron-Transmitting Structures: *Rama Venkatasubramanian*[1]; Edward Siivola[1]; Thomas Colpitts[1]; [1]Research Triangle Institute, Center for Semiconductor Research, 3040 Cornwallis Rd., Research Triangle Park, NC 27709 USA

We report a significant enhancement in the figure-of-merit (ZT) in the range of 3 at 300K in thin-film Bi2Te3/Sb2Te3 superlattice structures. The approach for ZT enhancement relies on what we call us phonon-blocking electron-transmitting structures (PBETS) as a way to reduce the lattice thermal conductivity, but maintain improved electrical transport properties. The factorial reduction in the lattice thermal conductivity, perpendicular to the SL interfaces in various structures, have been carefully studied and modeled using the 3-w method. The transmission line model (TLM) measurement has been developed to determine the electrical resistivity perpendicular to the SL interfaces in these structures. It appears that, for certain optimal SL structures, the electrical resistivities perpendicular to the periodic interfaces are essentially comparable to those in the in-plane direction. This observa-

tion is consistent with the modeling of the electronic contribution to thermal conductivities, in conjunction with Weide mann-Franz law, in these SL structures with subtle heterostructure-induced properties. The thermal conductivity values are consistent with the Peltier voltages measured across thermoelements processed using these superlattice structures under current pumping conditions as well. Thus, it appears that it is indeed possible to use such artificially-structured thin-film materials to obtain a significant enhancement in ZT compared to the state-of-the-art.

4:30 PM
Thermoelectric Quantum Dot Superlattices: *T. C. Harman*[1]; P. J. Taylor[1]; D. L. Spears[1]; M. P. Walsh[1]; [1]MIT Lincoln Laboratory, P.O. Box 73, Lexington, MA 02420-9180 USA

Since the experimentally observed increase of the Seebeck coefficient in PbTe/Pb1-xEuxTe in multiple quantum-well structures indicates the potential usefulness of low dimensionality, we have initiated an investigation of the thermoelectric properties of quantum-dot superlattices (QDSL) [1]. The self-organization of pyramidal islands that spontaneously form during strained-layer epitaxial growth of PbSe/Pb1-xEuxTe superlattices results in the formation of three-dimensional (3-D) quantum dot (QD) PbSe crystals interlaced throughout the structure [2]. We expect to enhance the thermoelectric figure of merit (ZT) in predominantly two ways in QDSL structures. Firstly, the enormous density of dissimilar materials interfaces involving the wetting (well) layer, the matrix (barrier) layer, and dots (3-D carrier confinement layer) of the QDSL structure are expected to lower the lattice thermal conductivity to values below those attainable by merely alloying [3]. Secondly, the Seebeck coefficient should be greatly enhanced within the dots due to carrier confinement in all three dimensions, which leads to a huge increase in the density of states. As a first step to realizing very large improvements in the ZT of a thermoelectric material, we will report on the growth and characterization of QDSL structures with up to 722 periods. Vertically stacked Bi-doped PbTe/PbSe0.98Te0.02 QDSL structures were grown by molecular beam epitaxy (MBE) on insulating (111) BaF2 substrates. The typical superlattice (SL) structures consisted of 200?400 vertically stacked Bi-doped PbSe0.98Te0.02 dot arrays each on an approximately 2-monolayer-thick wetting layer, while the thickness of the Bi-doped PbTe matrix layers were varied from 15 to 30 nm. The various dot arrays ranged from somewhat disorganized (for some growth conditions) to nearly perfect hexagonal arrangements (for other growth conditions). Atomic force microscopy images of the QDs show that the QD height can be as high as 13 nm, so the in-plane lattice thermal conductivity may be significantly reduced in these structures. Even though the equivalent homogeneous alloy composition can be over 25 % PbSe, electron mobilities are high, typically in the range 700?800 cm2/V-sec at 300 K. The thermoelectric power factor of the PbSeTe-based QDSL structures can be higher than that of high-quality bulk PbTe. The Seebeck coefficients can be enhanced even more than the recently reported increases in the PbTe/Te SL structures [4]. Characterization results will be reported, which include atomic force microscopy, scanning electron microscopy, transmission electron microscopy, x-ray diffraction, Hall coefficient, electrical resistivity, Seebeck coefficient, and thermal conductivity data. To date, we have obtained ZT values as high as 0.8 at 300 K and estimated ZT values as high as 1.9 at 580 K in these thermoelectric QDSL structures. [1] T. C. Harman, D. L. Spears, M. J. Manfra, J. Electron. Mater. 25, 1121(1996); L. D. Hicks, T. C. Harman, X. Sun and M. S. Dresselhaus, Phys. Rev. B 52, R10493 (1996). [2] G. Springholz, V. Holy, M. Pinczolits, and G. Bauer, Sci. 282, 734(1998). [3] G. Chen and M. Neagu, Appl. Phys. Lett. 71, 2761(1997). [4] T. C. Harman, D. L. Spears, and M. P. Walsh, J. Electron. Mater. Lett. 28, L1(1999); *This work was sponsored by the Defense Advanced Research Projects Agency (DARPA), Dept. of the Navy, and the Army Research Office under AF Contract No. F19628-95-0002. The opinions, interpretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force.

4:50 PM
Temperature Dependence of Thermionic Emission Cooling in Single Barrier and Superlattice Heterostructures: *Ali Shakouri*[1];

Chris LaBounty[2]; Patrick Abraham[2]; Yi-Jen Chiu[2]; John E. Bowers[2]; [1]University of California, Jack Baskin School of Eng., 1156 High St., Santa Cruz, CA 95064 USA; [2]University of California, ECE Dept., Santa Barbara, CA 93106 USA

Thermionic emission current in heterostructures can be used to make solid state coolers integrated with electronic and optoelectronic devices. In thermionic emission process, hot electrons from a cathode layer are selectively emitted over a barrier to the anode junction. Since the energy distribution of emitted electrons is almost exclusively on one side of Fermi energy, when current flows, strong carrier-carrier and carrier-lattice scatterings tend to restore the quasi-equilibrium Fermi distribution in the cathode by absorbing energy form the lattice, and thus cooling the emitter junction. The performance of the device can be optimized at various temperatures and for different cooling powers by changing the height and thickness of the barrier layer. Theoretical predictions show that single stage devices can provide by up to 10-30 degrees of cooling over a few microns thick barriers. Furthermore, the cooling efficiency can be enhanced by as much as an order of magnitude comparing to the bulk thermoelectric properties by using high barriers and highly degenerate superlattice structures. In order to investigate this effect experimentally, various single barrier (InGaAsP) and superlattice (InGaAs/InP and InGaAs/InAlAs) devices were grown using metal organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). The barriers 1-3 μm thick were surrounded by n+ InGaAs cathode and anode layers. Mesas with an area of 2500-20,000 square microns were etched down using dry etching techniques. Ni/AuGe/Ni/Au was used for top and bottom contact metallization. Total cooling on top of the device as well as substrate heating was monitored as a function of current. Despite the poor performance of the heat sink on the anode side (thermal resistance on the order of 250 K/W), a net cooling of 0.1-0.6C is observed on top of the devices for a current of 50-300 mA at 20°C heat sink temperature. This cooling over 1-3 microns thick barrier corresponds to cooling capacities on the order of 100's of W/cm2. The net cooling is increased by as much as a factor of two when the heat sink temperature is raised to 80°C. The temperature dependence of various parameters (thermionic emission cooling, thermal conductivity, and mobility) is analyzed and prospects for integrated cooling at low temperatures discussed.

Session W. Epitaxy of III-V

Friday AM
July 2, 1999

Room: Corwin East
Location: University Center

Session Chair: Jenn-ming Kuo, Bell Labs, Murray Hill, NJ USA

8:20 AM +
Structural and Optical Properties of Strained InGaAs/GaAs Quantum Wells Grown by MOVPE on (111)A GaAs Substrates:
Soohaeng Cho[1]; A. Majerfeld[1]; A. Sanz-Hervás[1]; B. W. Kim[4]; C. Villar[2]; Jongseok Kim[1]; [1]University of CO, Dept. of Elect. and Comp. Eng., CB425, Boulder, CO 80309 USA; [2]E.T.S.I. Telecomunicación, UPM, Departamento de Tecnología Electrónica, Ciudad Universitaria, 28040 Madrid, Spain; [4]Electronics and Telecommunications Research Institute, P.O. Box 106, Yusong, Taejon, 305-600 Korea

The growth of compound semiconductor structures in the non-conventional <111> crystallographic directions has received increased attention due to their special properties and potential for novel optoelectronic devices. We have recently reported [1] the first successful fabrication of high quality GaAs/AlGaAs Multiple Quantum Well (MQW) structures on (111)A GaAs substrates by the Metalorganic Vapor Phase Epitaxy (MOVPE) process. In this work, we report the structural and optical properties of strained InGaAs/GaAs Quantum Wells (QW) grown by MOVPE on (111)A GaAs substrates. A distinctive property of <111>

strained QWs is the presence of a strong piezoelectric field in the wells with a concomitant effect on the barrier field. Strained InGaAs/GaAs QW structures with nominal well widths of 40 Å were grown by atmospheric pressure MOVPE on (111)A GaAs. A High Resolution X-Ray Diffractometry (HRXRD) study was carried out to accurately determine the QW structural parameters. Room-temperature Photoreflectance (PR) spectroscopy, which permits the observation of higher interband transitions, was used to assess the abruptness and uniformity of the QW heterointerfaces. The PR spectra show all the possible interband transitions and, also, Franz-Keldysh oscillations, which were analyzed to obtain the electric field in the barriers. A theoretical computation appropriate for <111> oriented structures, incorporating the piezoelectric field in the wells, as well as the modified barrier field, was used to obtain all the confined electron and hole energies and, thereby, interpret the PR analysis. The theoretically calculated transition energies are in very close agreement with those experimentally obtained by fitting the PR spectra even up to the highest possible transitions for these wells. From a detailed well width Monolayer (ML) analysis, it is demonstrated that the QW interfaces have ±1 ML roughness and that the interfaces are very abrupt and uniform. Photoluminescence (PL) measurements were also used to further assess the optical quality and interface quality by determining the Full-Width-at-Half-Maximum (FWHM) values. A PL FWHM of 9.1 meV was observed, which corresponds to at most a ±1 ML fluctuation in well width. To our knowledge, this is the first demonstration of very high quality MOVPE grown InGaAs/GaAs QW structures on (111)A GaAs substrates. [1] "Effect of the Growth Parameters on the Luminescence Properties of High-Quality GaAs/AlGaAs Multiquantum Wells on (111)A Substrates by Metal Organic Vapor Phase Epitaxy," A. Sanz-Hervás, Soohaeng Cho, Jongseok Kim, A. Majerfeld, C. Villar, and B.W. Kim, J. of Crystal Growth, 195, 558 (1998).

8:40 AM +
An Investigation on the Mechanisms Responsible for Ar+-Laser Induced Growth Enhancement Of GaAs by Chemical Beam Epitaxy:
Bin Q. Shi[1]; Charles W. Tu[1]; [1]University of California, San Diego, Dept. of Elect. and Comp. Eng., 9500 Gilman Dr., La Jolla, CA 92093-0407 USA

Deposition of thin epitaxial films is required for the fabrication of many microelectronic devices. Often, these layers must be patterned by photolithographic processes, whereupon further layers are deposited to build up complex structures. Selected-area growth of thin films would greatly simplify this procedure. Consequently, there has been considerable interest in using external energy sources such as lasers and ion beams to stimulate growth. Several studies of Ar+ laser-assisted chemical beam epitaxy (CBE) of GaAs have been reported in the literature. For example, our group previously reported growth enhancement in the growth temperature range of 250°C to 450°C using a 488-nm Ar+ laser and triethylgallium (TEGa) and tris(dimethylamino) arsenic (TDMAAs) as precursors. It was concluded in those studies that the mechanisms responsible for the growth rate enhancement were of a photolytic and/or pyrolytic nature. Catalytic (or electrochemical) mechanisms were ruled out because no dependence of the growth rate enhancement on the substrate type (n-type, p-type or semi-insulating) was observed. However, there were several important questions unanswered, such as, 1) what physical processes dictate the temperature window for growth enhancement? 2) which species undergo photodecompsition, the intermediate decomposition products or the parent molecules? and where are they, in the physisorption state or chemisorption state? 3) how large would the photo absorption cross sections have to be to account for the enhancement? and 4) what are the likely photodecomposition reaction pathways? To answer these questions, we developed a numerical model for GaAs CBE with TEGa and TDMAAs. We demonstrated there that properly combining reaction mechanisms derived from surface-science desorption studies enabled us to predict well the growth rate without adjustable parameters. In this report, based on the correlation between simulated variations of concentrations of surface species with temperature and the observed temperature window of growth enhancement, we show that photodecomposition of chemisorbed diethylgallium (DEGa), along with laser-induced temperature rise, is responsible for the growth enhancement. The surface coverage of DEGa is governed by the availability of unoc-

cupied surface sites and the competition for initial physisorption on the GaAs surface between TEGa and TDMAAs. The photo absorption cross section required to reproduce the growth enhancement is found to be two orders of magnitude smaller than the typical value of UV absorption peaks of metalorganic species. One of the major photodecomposition pathways of DEGa is proposed to be light-induced dissociation involving the b-hydrogen elimination. * This work is partially supported by the Air Force Wright Laboratory (Contract No. F33615-95-C-5441).

9:00 AM

Enhancement of Electron Mobilities in Pseudomorphic In$_{0.7}$Ga$_{0.3}$As/In$_{0.52}$Al$_{0.48}$As Modulation-Doped Quantum Wells with (411)A Super-flat Interfaces Grown by Molecular Beam Epitaxy: *Takahiro Kitada*[1]; Masato Ueno[1]; Toyohiro Aoki[1]; Satoshi Shimomura[1]; Satoshi Hiyamizu[1]; [1]Osaka University, Graduate School of Eng. Sci., 1-3 Machikaneyama, Toyonaka, Osaka 560-8531 Japan

InP-based pseudomorphic InGaAs/InAlAs modulation-doped quantum wells (MD-QWs) with high two dimensional electron gas (2DEG) mobilities promise for high-frequency and low-noise device applications. In order to enhance 2DEG mobility in the pseudomorphic MD-QW, it is necessary to suppress interface roughness scattering. In recent years, we have reported that atomically flat interfaces over a macroscopic area (super-flat interfaces) can be formed in In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As QWs lattice-matched to (411)A InP substrates by molecular beam epitaxy (MBE). In this paper, we report higher 2DEG mobilities in pseudomorphic In$_{0.7}$Ga$_{0.3}$As/In$_{0.52}$Al$_{0.48}$As MD-QWs grown on (411)A InP substrates than those of conventional In$_{0.7}$Ga$_{0.3}$As/In$_{0.52}$Al$_{0.48}$As MD-QWs grown on (100) InP substrates by MBE. In$_{0.7}$Ga$_{0.3}$As/In$_{0.52}$Al$_{0.48}$As MD-QWs were grown on the (411)A InP substrates at $T_s = 540$℃ under V/III = 8 (in pressure). Well widths of the In$_{0.7}$Ga$_{0.3}$As channel layers were 12, 14, 16, and 18 nm. A Si-doped InAlAs ($N_D = 1 \times 10^{18}$ cm^{-3}) and the InGaAs channel layer were separated by a 6 nm-thick undoped InAlAs spacer layer. 2DEG mobility (m_{2DEG}) in the (411)A MD-QW with $L_w = 12$ nm was 181,000 cm^2/Vs ($N_s = 1.5 \times 10^{12}$ cm^{-2}) at 24 K, which was 38% larger than that ($m_{2DEG} = 131,000$ cm^2/Vs) of a corresponding (100) MD-QW sample. Observed values of m_{2DEG} were compared with calculated m_{2DEG} at low-temperature based on an elastic scattering theory. We took into account of ionized impurity scattering, alloy disorder scattering, and interface roughness scattering for the calculation. The interface roughness was assumed to be characterized by the Gaussian fluctuations with the average height D and the lateral size L. Higher m_{2DEG} in the (411)A MD-QWs with $L_w = 12$-18 nm can be explained well by a small interface roughness (D = 0.4 nm), which is much smaller than that (D = 0.7 nm) of the (100) samples with $L_w = 12$-16 nm. A drastic decrease of m_{2DEG} for the (100) MD-QW with $L_w = 18$ nm is due to a smaller critical thickness of the pseudomorphic (100) InGaAs. This result indicates that InGaAs/InAlAs MD-QWs grown on (411)A InP substrates by MBE are suitable for high-frequency and low-noise devices because of their higher electron mobility due to the (411)A super-flat interfaces.

9:20 AM

High Quality GaAs0.68P0.32/In0.13Ga0.87P/Si QW Structure with a Very Few Threading Dislocations: *Yasuhiro Fujimoto*[1]; Hiroo Yonezu[1]; Naoki Ohshima[1]; Kenji Momose[1]; [1]Toyohashi University of Technology, Dept. of Elect. and Electr. Eng., 1-1 Hibarigaoka, Tempaku-cho, Toyohashi, Aichi 441-8580 Japan

The growth of high quality III-V compound semiconductors on Si substrate is a key technology for realization of optoelectronic integrated circuits (OEICs). However, a large number of threading dislocations are generated in GaAs epilayers on Si substrates. It is mainly attributed to a large lattice mismatch of 4% between GaAs and Si. These threading dislocations must be eliminated, since they degrade their performances during operation of minority carrier devices such as laser diodes and light-emitting diodes. Then, we proposed a structure of GaAs0.68P0.32/In0.13Ga0.87P/GaP/Si as a novel quantum well (QW) structure with a small lattice mismatch (1.4%) to Si. The QW structure was theoretically optimized to obtain a conduction band offset at small lattice-mismatch enough for CW lasing at room-temperature (RT). We have tried to form the QW structure and observed a normal photolumi-

nescence (PL) as well as a very few threading dislocations. The epitaxial growth was carried out by all solid-source molecular beam epitaxy. Firstly, a 300 nm thick GaP layer was grown on Si (100) substrate misoriented by 4?? toward the [011] direction to form a GaP/Si structure. A lattice mismatch between Si and GaP layers is 0.4%. Then, the GaAs0.68P0.32/GaAs0.27P0.73/In0.13Ga0.87P QW structure was grown on the GaP/Si structure. A lattice mismatch between the GaP and In0.13Ga0.87P cladding layers is 1%. The In0.13Ga0.87P cladding layer is lattice-matched to the GaAs0.27P0.73 guiding layer. The GaAs0.68P0.32 QW contains a compressive strain of 1.5%. The thickness of the QW was chosen to be less than a critical thickness to prevent the generation of misfit dislocations. Cross-sectional images of transmission electron microscope revealed that no dislocations were generated in a region around 50 um length along the QW structure. Such number of dislocations is the smallest as far as we know. The lattice mismatch of 1.4% was accommodated at the In0.13Ga0.87P-GaP and the GaP-Si hetero-interfaces by introducing misfit dislocations. The quality and structural profile of GaAsxP1-x epilayers can be improved by varying the As flux quickly. The period of the growth interruption was decreased to about 10s in the growth of the GaAs0.68P0.32/GaAs0.27P0.73. As a result, strong band-edge emission was observed from the GaAs0.68P0.32 QW at RT. It was also found by secondary ion mass spectroscopy that the abrupt hetero-interfaces were formed in the QW heterostructure of GaAs0.68P0.32/GaAs0.27P0.73/In0.13Ga0.87P. When the period of the growth interruption is increased, no PL emission was observed in the GaAs0.68P0.32 QW at RT. It was also clarified that the As composition was decreased in the QW and that the hetero-interfaces were spread between the QW and guiding layer. These results indicate that a highly reliable and performed GaAs0.68P0.32/In0.13Ga0.87P laser diode could be realized on a Si substrate.

9:40 AM +

Dependence of Cracker Temperature to Silicon Doing Concentration in InGaAlP Layers Grown by Solid Source Molecular Beam Epitaxy: *Yi-Cheng Cheng*[1]; Kuochou Tai[1]; S. T. Chou[2]; K. F. Huang[3]; *W. J. Lin*[4]; *W. H. Lan*[4]; A. C. H. Lin[4]; *T. C. Wang*[4]; [1]National Chiao-Tung University, Institute of Opto-Elect. Eng., 1001, Ta-Hsieh Rd., HsinChu, Taiwan ROC; [2]Chung-Cheng institute of Technology, Dept. of Elect. Eng., Tahsi, Taoyuan, Taiwan ROC; [3]National Chiao-Tung University, ElectroPhysics Dept., 1001,Ta-Hsieh, HsinChu, Taiwan ROC; [4]Chung Shang Institute of Sci. and Technology, Material R & D Center, Lun-Tang P.O. Box 90008-8-6, Taoyuan, Taiwan ROC

In molecular beam epitaxy (MBE), both As4 and As2 are commonly used as arsenic sources to grow GaAs and AlGaAs epitaxial layers. A strong dependence of Si doping efficiency on As2/As4 flux ratio and substrate temperature was also observed in GaAs and InAlAs films. Although the dependence of arsenic dimer and tetramer to silicon incorporation efficiency were noticed, none of the effect of phosphorus species on silicon doping efficiency has been reported. Since the valve cracker solid source phosphorus cell was invented, all solid source molecular beam epitaxy (SSMBE) had been widely used to grow phosphorus-related compound semiconductor. In this study, we found that the Si doping efficiency in InGaAlP epilayers grown by SSMBE has a strong dependence on the phosphorus cracker temperature and a slightly weaker dependence on the growth temperature. Samples with Si-doped In0.5(Ga0.3Al0.7)0.5P epitaxial layer were grown in a RIBER 32P system equipped with phosphorus and arsenic valved crackers. Two sets of samples were prepared. The first set is a series of "staircase" structures, which have several InGaAlP layers grown sequentially with the same Si cell temperature but various phosphorus cracker and substrate temperatures. The second set has a structure consisting of a 1000nm Si-doped InGaAlP layer grown at various substrate temperatures and P4/P2 ratios. The P4/P2 flux ratio was adjusted by changing the P-cracker temperature. The composition and electrical properties of all the samples were studied by double crystal X-ray diffractometry (DCXD), photoluminescence (PL), Hall, electrochemical C-V methods and secondary ion mass spectrometry (SIMS). We observed that the substrate temperature and the cracking efficiency of phosphorus affected the Si doping characteristics prominently. The carrier concentrations of these InGaAlP samples clearly indicate that the doping concentration is

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strongly dependent on the growth temperature and the phosphorus cracker temperature. No matter how the growth temperature changes the Hall concentration of the Si-doped InGaAlP layer increases with the decreasing phosphorus cracker temperature. Although the silicon counts in the SIMS profile showed a constant value, both the C-V and Hall measurements showed that the dimer phosphorus as well as the substrate temperature had a tendency to reduce the effective Si doping concentration. However, the dependence of Si-doping efficiency on the substrate temperature is not as strong as that on the phosphorus species when the growth temperature is low. The amphoteric behavior of Si may be the major mechanism in the variation of its doping efficiency in InGaAlP.

10:00 AM Break

Session X. Composite Materials and Applications

Friday AM   Room: Corwin East
July 2, 1999   Location: University Center

Session Chairs: Daniel Docter, HRL Laboratories, Malibu, CA USA; Jerry Woodall, Yale University, New Haven, CT USA

10:20 AM +
Transit Time and Light Absorption Effects in ITG-GaAs and Applications to MSM-Photodetectors: *Vijay Krishnamurthy[1]; Marian C. Hargis[2]; Michael R. Melloch[2]; [1]Purdue University, School of Elect. and Comp. Eng., Mailbox #258, West Lafayette, IN 47907-1285 USA; [2]Purdue University, School of Elect. and Comp. Eng., West Lafayette, IN 47907-1285 USA*

Reduced temperature growth of GaAs by molecular beam epitaxy (MBE) incorporates excess arsenic into the crystal. With anneal this excess arsenic precipitates. The resulting arsenic precipitates and residual defects reduce the carrier lifetime. Low temperature grown (LTG) GaAs, which has about 1% excess arsenic, has a carrier lifetime of about 1 ps. Controlling the growth temperature, and hence controlling the excess arsenic concentration, the carrier lifetime can be controlled. We have used this control of the carrier lifetime to tailor material for applications as metal-semiconductor-metal (MSM) photodetectors (PDs). Using intermediate temperature growth (ITG), the lifetime can be controlled so that it is a little longer than the transit time between electrodes. This removes the slow tail response typical of the impulse response of MSMs, yet does not significantly reduce the responsivity. Since the MSM photodetector has a lower capacitance per unit area than a PiN photodetector, large-area high-speed photodetectors are possible. The samples in this study consist of a 1 micron thick ITG-GaAs light absorption layer grown at 400°C by MBE, which contains about 0.02% excess arsenic. On top of this a 30 nm thick layer of $Al_{0.3}Ga_{0.7}As$ was grown to improve the surface mobility and the structure was capped with a $Al_{0.5}Ga_{0.5}As$ layer. The samples were then annealed at a temperature of 800°C. MSM-PDs with finger spacing varying from 2 microns to 6 microns were then fabricated by depositing 1 micron wide Ti-Au fingers using standard photolithography and lift-off techniques. The light absorption region of the device has a square geometry with an area of 400 microns X 400 microns. The devices were contacted using a ground-signal-ground pad arrangement. The 6 micron spacing MSM had a FWHM of 93 ps (3.76 GHz Bandwidth) and a fall time of 173 ps for its temporal response. The devices studied also had dark current densities in the range of 4.2 fA/micron[2] and responsivities in the range of 0.12 to 0.22 A/W. Both the temporal response and dark currents demonstrates dramatic improvement for large-area detectors. The reduced lifetime of the ITG-GaAs light-absorption region and the reduced device capacitance of the MSM structure have improved the temporal response of the detector. In fact, the devices reported here have twenty times the active area and twice the bandwidth of typical commercially available photodetectors. Thus, we have shown that ITG-GaAs is an excellent material for fabricating large-area MSM-PDs. This work has been supported by AFOSR grant F49620-96-1-0234A

10:40 AM +
Ultrafast Carrier Dynamics in Be-doped Low Temperature Grown GaAs Studied by Double-pulse Excitation: *Ri-an Zhao[1]; Petra Specht[1]; Eicke R. Weber[1]; Nen-Wen Pu[2]; Jeff Bokor[2]; [1]University of California-Berkeley, Dept. of Mats. Sci. and Eng., 211-226 Cory Hall #1772, Dept. of EECS, Berkeley, CA 94720 USA; [2]University of California, Dept. of Elect. Eng. and Comp. Sci., Berkeley, CA 94720 USA*

Low temperature grown (LT) GaAs exhibits ultrashort carrier lifetime due to a high concentration of carrier trapping centers induced by the incorporation of excess As. Though the short carrier lifetime is essential to many optoelectronics and laser Sci., the trap recovery time can limit the device maximum repetition rate. In this paper, we studied Be-doped LT-GaAs, which is thermally stabilized and has subpicosecond carrier lifetime, by using time-resolved reflectivity and transmission experiments. By two time-delayed femtosecond pulse excitation at various carrier density levels, the carrier photoresponse can be enhanced by a factor of 2. The second photoresponse decay time is longer (but still within ~1ps) after the first pulse excitation. This is because the trapping efficiency of As-related defects is decreased due to the occupation of fast-trapped electrons from the first pulse. It will be shown that by careful material design, both ultrashort carrier lifetime (<1ps) and improved trap recovery time (~3ps) could be achieved.

11:00 AM +
Experimentally Verified Conduction Model for a Low-Resistance Non-Alloyed Ohmic Contact Utilizing Low-Temperature-Grown GaAs: *N.-P Chen[1]; H. J. Ueng[2]; D. B. Janes[2]; K. J. Webb[2]; M. R. Melloch[2]; [1]Purdue University, Dept. of Phys., 1396 Phys. Bldg., West Lafayette, IN 47907 USA; [2]Purdue University, School of Elect. and Comp. Eng., 1285 Elect. Eng. Bldg., West Lafayette, IN 47907 USA*

Non-alloyed ohmic contacts to GaAs devices utilizing a low temperature grown GaAs (LTG:GaAs) cap layer have shown their merit in terms of low contact resistance and a planar injector interface, making the devices suitable for contacts to shallow devices and nanoelectronic devices [1,2]. A specific contact resistance on the order of 10^{-7} W-cm[2] has been achieved, comparable to the best contacts to date for GaAs. In order to explain the measured behavior and to guide further development, a conduction model is needed. In particular, it is important to understand the role of the LTG:GaAs in the electron transport that provides this low contact resistance. In this presentation, we will show results from a model that supports experimental data for contact resistance versus temperature. The model considers the energy barrier in the contact structure as a modified Schottky barrier, incorporating the characteristics of the LTG:GaAs and the n++ layers. Such a modified Schottky barrier approach provides a simple way to calculate the contact resistance. A numerical Poisson equation solution of the barrier profile is calculated considering the mid-gap defect states of the LTG:GaAs layer and the surface potential of the layer. This barrier is approximated with a Schottky barrier with a uniform effective doping density so that the established Schottky barrier contact resistance formulation can be utilized. This formulation considers three electron transport regimes: field emission (FE), thermionic field emission (TFE), and thermionic emission (TE) [3]. A series of measurements of contact resistance with different n++ layer doping densities and different temperatures shows the consistency of the model. A comparison of measured results and the calculations based on typical parameter sets shows that tunneling processes (FE and TFE) dominate for operation near room-temperature. It also shows that the low contact resistance is due to high activated donor density ($> 5 \times 10^{19}$ cm[-3]) in the space charge region of the n++ Si-doped layer and a surface potential energy approxi-

mately 0.3-0.5 eV above the Fermi level. These two effects are associated with the defect states due to excess As incorporated into the LTG:GaAs. Both features are in contrast to the behavior expected for stoichiometric GaAs layers, in which the bulk activated donor density is limited to ~ 5x10^18 cm^-3 and the surface Fermi level pins near mid-gap. The modeled results provide insight about the performance of low resistance non-alloyed ex-situ contacts to semiconductor device layers. Reference: [1] M. P. Patkar, et al., Appl. Phys. Lett. 66, 1412 (1995); [2] H. J. Ueng, et al., Appl. Phys. Lett. 71, 2496 (1997); [3] K. Varahramyan, et al., Solid State Electronics 39, 1601 (1996).

11:20 AM +
Thermal Conductivity of Low-Temperature-Grown GaAs: *Andrew W. Jackson*[1]; James P. Ibbetson[2]; Arthur C. Gossard[1]; Umesh K. Mishra[2]; [1]University of California, Mats. Dept., Santa Barbara, CA 93106 USA; [2]University of California, ECE Dept., Santa Barbara, CA 93106 USA

Thermal conductivity of low-temperature-grown (LTG-GaAs) was measured by observing the temperature rise of a self-heated, photolithographically patterned platinum wire on the surface of the sample. The temperature rise of the wire is determined by the thermal conductivity of the epilayer, the thermal conductivity of the substrate, and the geometry of the sample (layer thickness and wire width). To extract the bulk thermal conductivity of the LTG-GaAs layer from the measured temperature rise, the Laplace equation was solved numerically for our specific sample geometry. Thermal conductivity of LTG-GaAs was measured as a function of growth and annealing conditions. All samples were grown by MBE using diffuse reflectance spectroscopy to measure and control substrate temperature. Annealing was performed both ex-situ by rapid thermal annealing, and in-situ under As$_2$ flux in the MBE system. Thermal conductivity of un-annealed LTG-GaAs grown at 240°C was found to be only about 1/4 of the value for stoichiometric GaAs. By measuring samples grown at several growth temperatures, we have found that the excess thermal resistance in un-annealed LTG-GaAs is correlated with the excess As concentration of the material. Upon annealing the LTG-GaAs at or above 550°C, the thermal conductivity of the material increases, although it is still lower than the value for stoichiometric GaAs. Higher annealing temperatures generally resulted in a larger thermal conductivity increase, although no further increase was observed at anneal temperatures beyond 650°C. Calculations show that strong phonon scattering by point defects (primarily As antisites) can account for reduced thermal conductivity in the as-grown material. After annealing, the reduction in point defects leads to an increase in thermal conductivity, although this increase is less than we expect based on current understanding of point defects and precipitates in annealed LT GaAs.

11:40 AM
Surface Atomic Process of Incorporation of Excess Arsenic in Molecular Beam Epitaxy of GaAs: A. Suda[1]; *N. Otsuka*[1]; [1]Japan Advanced Institute of Science and Technology, School of Mats. Sci., Asahidai -1, Tatsunokuchi, Nomigun, Ishikawa 923-1292 Japan

GaAs layers grown by molecular beam epitaxy (MBE) in a temperature range between 200 and 300°C (LT-GaAs) contain excess As up to about 1 atomic percent, but possess high crystalline quality. According to reported equilibrium phase diagrams of GaAs, the solid solubility limit of excess As in GaAs is only about 0.1 atomic percent at most even near the melting point. The high concentration of excess As in LT-GaAs, therefore, is considered to result from a unique surface process of the MBE growth. The incorporation process of excess As in LT-GaAs was studied by varying As fluxes in a temperature range between 200 and 310°C. Concentrations of excess As in GaAs layers were estimated by measuring increases of lattice spacings with X-ray diffraction, and the substrate surface temperature was monitored by using a quartz rod connected to an infrared pyrometer with its end placed in the vicinity of the substrate surface. Nearly stoichiometric GaAs layers without any detectable increase of the lattice spacing are grown at all substrate temperatures under the As atom flux equal to the Ga atom flux. With an slight increase of the As flux from the above stoichiometric condition, the concentration of excess As sharply increases for all substrate temperatures. For all growth temperatures, there is a tendency of saturation of the concentration of excess As with increasing

the As atom flux, where the saturated concentration decreases with the growth temperature. Based on the results, a model is presented for surface atomic processes of incorporation of excess As into a GaAs epilayer. In the model, As atoms which are chemisorbed on the As-terminated GaAs (100) surface serve as a precursor of excess As. On attachment of Ga atoms to the surface the majority of chemisorbed As atoms desorb, but few atoms are incorporated as antisite As atoms. The model explains the saturation of the concentration of excess As for high As fluxes and a temperature-dependence of the saturated concentration. The support for the model is provided by an atomic structure of a reconstruction which occurs in the GaAs (100) surface at low temperatures under high As flux as well as by a Langmuir-isotherm-like variation of the concentration of excess As with the As flux.

Session Y. Properties of Quantum Wires and Wells

Friday AM   Room: Corwin West
July 2, 1999   Location: University Center

Session Chairs: Jim Merz, University of Notre Dame, Notre Dame, IN USA; Clivia Sotomayor-Torres, University of Wuppertal, Institute of Mats. Sci. & Dept. of Elect. Eng., Wuppertal, Germany

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8:20 AM
Structural and Alloy Composition Uniformity of InGaAs Ridge Quantum Wires Grown by Selective MBE on Patterned InP Substrates: *Chao Jiang*[1]; Hajime Fujikura[1]; Tsutomu Muranaka[1]; Hideki Hasegawa[1]; [1]Hokkaido University, Research Center for Interface Quantum Electronics and Graduate School of Electronics and Information Eng., North 13, West 8, Kita Ku, Sapporo, Hokkaido 060-8628 Japan

For realizing future electronics based on quantum devices, formation of arrays of high quality and highly uniform quantum wires and dots is one of the key issues. Recently, we have demonstrated that selective MBE growth of InGaAs/InAlAs ridge quantum wire (QWR) arrays on the mesa-patterned InP substrates is promising for this purpose. The purpose of this paper is to investigate the structural and alloy composition uniformity of the InGaAs/InAlAs QWRs using photoluminescence (PL), cathodoluminescence (CL), transmission electron microscopy (TEM) and energy dispersive x-ray microanalysis (EDX) techniques. Selectively grown InGaAs QWR arrays having wire widths within a decananometer range showed narrow, intense PL emission peaks as well as continuous, uniform emission lines in the CL images due to the wires. Particularly, the observed narrow peak width (FWHM = 28mev) of macroscopic PL indicated that the uniformity of the present QWR was the best of all the InP-based InGaAs QWRs formed by selective growth techniques reported so far, and better or comparable to most of the GaAs-based selectively grown QWRs reported so far. However, by fitting the PL peak width data to the theoretical values calculated by assuming existence of certain size and alloy composition fluctuations in the InGaAs QWRs, it was found that there still remained some residual structural and compositional imhomogeneity in the present InGaAs QWRs, which may become a serious problem in the scaled-down QWRs having widths below 10nm. A detailed cross-sectional TEM analysis revealed the presence of a few mono-layer (ML) fluctuation of the interface between the QWR and the top InAlAs barrier layers. On the other hand, the bottom interface of the QWR was nearly atomically sharp. Thus, fluctuation on the top interface appears to be the main cause of the wire nonuniformity observed by the PL peak width measurements. By feeding back the results of cross-sectional TEM observations to systematic change of MBE growth conditions, the optimum condition to grow QWRs with atomically sharp top and bottom interfaces was established. As for the composition unifor-

mity, the TEM and EDX analysis revealed presence of a region with unintentional compositional variation in the QWR structure. Namely, in the vicinity of the vertical plane which contains the ridge and bisects the whole wire structure along the wire direction, In composition was found to be appreciably lower than those in surrounding InAlAs and InGaAs regions. Although a ridge structure is used here, the phenomenon looks quite similar to the so-called vertical quantum well observed in the GaAs/AlGaAs V-groove quantum wires grown by selective MOVPE. Detailed analysis of the spatial variation of the alloy compositions as well as the resultant spatial modulation of the electronic states within the wire structure will be discussed.

8:40 AM

Spin Splitting of Exciton Band in Asymmetric Double Quantum Wells: Guangyou Yu[1]; Xiwu Fan[1]; Jiying Zhang[1]; Dezhen Shen[1]; [1]Changchun Institute of Physics, Chinese Academy of Sciences, Laboratory of Excited State Processes, 1 Yan An Rd., Changchun, Jilin 130021 ROC

Tunneling mechanisms and processes have been intensively investigated in the asymmetric double quantum wells (ADQW) structure that consists of two different width wells coupled by a thin barrier[1,2]. Besides that, the Kramers degeneracy is lifted causing spin splitting to appear in the energy band in this structure because of the lack of spatial symmetry. Compound semiconductors in zinc-blende structure or some artificial quantum well structures (e.g. ADQW) do not have the inversion symmetry, and then the energy bands are split. Additionally, energy bands are also spin split by the spin-orbit coupling in the ADQW structure. The spin splitting feature of energy band in compounds or quantum well structures is usually observed under magnetic field condition, and the spin splitting is corresponding to the intrinsic lack of spatial symmetry of compounds or heterostructure[3,4]. In this paper, we study the spin splitting of the exciton band in ZnCdSe/ZnSe ADQW, where spatial symmetry can be designed artificially. The spin splitting was observed by photopumped stimulated emission spectra and Raman scattering spectrum without magnetic field. ZnCdSe/ZnSe ADQW sample was prepared by LP-MOCVD. Stimulated emission spectra and Raman scattering measurement were performed by a N2 laser and a YAG laser, respectively. For the stimulated emission measurement, the sample was cleaved to approximately 1 mm wide resonator, and the Fabry-Perot cavity was formed by the natural facets of the sample bar. The stimulated emission spectra showed two sets of oscillation modes, and the energy separation between the centers of the two sets of modes is only several meV. We exclude the situation that the two sets of modes are corresponding to two different exciton processes by analyzing lasing process and the exciton recombination mechanisms. Then the two sets of the oscillation modes were explained by the spin splitting of the n=1 heavy hole exciton band. We found the spin splitting arising from the lack of specular symmetry in this kind of structure depends on the excitation intensity strongly. The spin flip transition was also observed, and the spin flip transition can modulate the stimulated emission intensity of the two sets of the modes by the flip rate which depends on the excitation. Our explanation was proved by the Raman scattering spectrum further. References: [1] Ph.Roussignol, A.Vinattieri, L.Carraresi, M.Colocci, A.Fasolino, Phys.Rev.B44, 8873(1991) [2] S.Haacke, N.T.Pelekanos, H.Mariette, M.Zigone, A.P.Heberle, W.W.Ruhle, Phys.Rev.B47, 16643(1993) [3] B.Das, D.C.Miller, S.Datta, R.Reifenberger, W.P.Hong, P.K.Bhattacharya, J.Singh, M.Jaffe, Phys.Rev.B39, 1411(1989)[4] J.Luo, H.Munekata, F.F.Fang, P.J.Stiles, Phys.Rev.B38, 10142(1988)

9:00 AM

Mobility Edge and Exciton Relaxation in CdSe/ZnSe Quantum Wells: Jinxi Shen[1]; R. Pittini[1]; K. Yui[1]; I Souma[1]; Y. Oka[1]; E. Kurtz[2]; T. Yao[3]; [1]Tohoku University, Research Institute for Scientific Measurements, Katahira 2-1-1, Sendai, Miyagi 980-8577 Japan; [2]University of Karlsruhe, Institute for Applied Physics, Karlsruhe D-76128 Germany; [3]Tohoku University, Institute for Mats. Research, Katahira 2-1-1, Sendai, Miyagi 980-8577 Japan

The carrier relaxation rate to the band edge determines the efficiency, as well as the final operation energy of laser diodes. Mostly, laser diodes emit light coherently at the center of their luminescence spectra. In fact, the energy corresponding to the center of the photo-luminescence (PL) spectrum is close to the maximum PL intensity. Therefore, at this energy a considerable photon density is emitted. Moreover, in the energy range near the center of the PL spectrum the relaxation rate of the excitons varies significantly (mobility edge) yielding an efficient exciton accumulation. We report the transient PL (TRPL) spectra of CdSe/ZnSe multiple-single quantum wells (MSQWs) to exhibit the exciton relaxation around the mobility edge of the excitons. Five CdSe single quantum wells with 3.5, 2.5, 1.5, 1 and 0.5 monolayers are grown successively by atomic layer epitaxy (ALE) in one sample alternated by 12nm thick ZnSe barriers. The PL spectra of each quantum well are well separated with no spectral overlap. The line width of the five quantum wells decreases with decreasing well width. Thus, the well width fluctuations are strongly reduced by the ALE growth method and excitons are localized only by impurity potential. TRPL spectra are taken and analyzed at liquid helium temperature. For each quantum well, the PL decay time increases with decreasing recombination energy, suggesting an exciton relaxation from higher-energy to lower-energy states. Also the PL rise time increases with decreasing recombination energy, but it saturates around the peak of the time-integrated PL spectrum. Since the PL rise time represents the exciton build-up time, a saturated PL rise time indicates a reduced energy relaxation. We assign the observed phenomenon to a reduction of the carrier relaxation due to the three-dimensional confinement of the excitons below the mobility edge. The exciton relaxation to the band edge is usually accompanied with a movement in real space. However, in our case the impurity potential causes the band-edge fluctuations, therefore, the excitons are no more mobile below their mobility edge. They are three-dimensionally confined. Recently, theorists showed that three-dimensional confinement of the carriers reduces the relaxation rate due to the difficult matching between k vectors of the carriers and the acoustic phonons. Therefore, excitons relaxing to the band edge from higher energetic states can accumulate substantially around the mobility edge without going further to lower energetic states. They emit photons to form the PL peak that coincides usually with the exciton mobility edge. Under stimulated emission, the quickly recombining excitons are compensated by the excitons relaxing from higher energetic states and, in effect, do not relax significantly to deeper states below the mobility edge.

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Recombination Lifetime Measurements of InGaN/GaN Multiple Quantum Wells: Eun-joo Shin[1]; N. W. Song[1]; J. I. Lee[1]; D. Kim[1]; M. Y. Ryu[2]; P. W. Yu[2]; D. Lee[3]; Y. -H. Choi[4]; C. -H. Hong[5]; [1]Korea Research Institute of Standards and Science, Spectroscopy Group, Yusong-ku, P.O. Box 102, Taejon 305-600 Korea; [2]K-JIST, Dept. of Information & Communications, Kwangju 506-712 Korea; [3]Chungnam National University, Dept. of Phys., Taejon 305-764 Korea; [4]L. G. CIT, Optoelectronics Group, Seoul 137-140 Korea; [5]Jeonbuk National University, SPRC, Jeonju 560-756 Korea

Recently there has been a considerable amount of research towards the understanding of fundamental optical properties of III-nitride semiconductors. However many important materials remain to be investigated. In this paper, the recombination lifetimes of InGaN/GaN multiple quantum wells grown by metal organic chemical vapor deposition (MOCVD) have been studied at various time domains by time-resolved spectroscopy. Slow recombination decay component that has the lifetime of several hundred ns was observed for the first time. InGaN/GaN multiple quantum well sample was grown by vertical rotating disk MOCVD. This sample has 75 A-thick undoped $In_xGa_{1-x}N$ (x ~ 0.18) active wells and 60 A-thick Si-doped GaN barriers. Two kinds of time-resolved photoluminescence measurements were employed. The one is time-correlated single photon counting (TCSPC) technique which enables the lifetime measurement in the range from a few tens of ps to ns. For longer lifetime measurement, a Q-switched Nd:YAG laser pumped dye laser was used as an excitation source. A 500 MHz digital storage oscilloscope (HP 54503A) monitored the temporal profile. The lifetime measurement range is a few tens of ns to ms. We obtained the PL decay profiles at various emission energies using TCSPC system as shown in Fig. 1(a). As the emission energy increases, the PL decay becomes faster. The decay profiles were well described by a two-exponential function with fast (t_1) and slow (t_2) decay components. And we can also observe that the background component (t_3) increases with

decreasing emission energy. This means there exists a much slower recombination decay. This slower decay (t_3) was measured by using a ns pulse laser. The decay profiles of this background component at various emission energies are shown in Fig. 1(b). The temporal responses become faster as the emission energy increases. The decay time is in the range of several hundred ns. The short components represent the decays of t_1 and t_2. From these time-resolved data we can consider that the PL peak of InGaN active well in the inset of Fig. 1(a) consists of three different emissions. The decay time of t_1 from the fitting result is almost constant in the energy range from 2.75 to 3.00 eV with 300 ps, and decreases down to 150 ps with increasing emission energy. The amplitude of t_1 decay is always greater than that of t_2. Together with the red shift of time-resolved photoluminescence spectra with increasing delay time, we interpreted this main emission as the recombination of localized excitons. The decay of t_2 decreases from 2.1 to 0.9 ns as the emission energy increases. This component may be an impurity-related peak, which is not clear at this stage. When we plotted the emission energy dependence of recombination lifetime t_3 of the background component, the decay time decreases monotonously from 1280 to 140 ns with increasing emission energy. From the experimentally observed emission energy dependence of the decay time t_3 and relation for the radiative recombination lifetime of a band-to-impurity transition, the fitted E_0 value of 3.06 eV is in agreement with the bandgap energy E_g of 3.04 eV. This dynamic feature suggests this slower decay component as due to the band-to-impurity transitions. The impurity may be related to the Si donor which exists in GaN barrier layer together with alloy disorder or the interface roughness.

9:40 AM
Study of Temperature-Dependent Photocurrent and Dark Current Measurements for a Maximization of Carrier Collection and a Voltage Enhancement of MQW p-i-n Diodes: *Cedric Monier*[1]; *Frederick Newman*[1]; Inna Serdiukova[1]; Lissandro Aguilar[1]; Mauro F. Vilela[1]; Alexandre Freundlich[1]; [1]University of Houston, Space Vacuum Epitaxy Center, 4800 Calhoun St., Sci. & Research I, Houston, TX 77204-5507 USA

Multi-quantum well (MQW) heterostructures, by exhibiting stronger absorption properties than in bulk materials, have attracted much attention in recent years due to their potential application for optoelectronic devices such as optical modulators, lasers or solar cells. For the latest photoconverter application, the quantum well-based technology which consists of the introduction of a periodical multi-quantum well heterostructure between the p and n-doped regions of a conventional single band gap has been studied to enhance the power conversion efficiency. The desired effect is to increase the carrier generation and the photocurrent output by extending the absorption properties below the band gap of the basic material. The insertion of MQWs into the depletion region has been invariably accompanied at room-temperature by a reduction of the voltage output resulting from the development of carrier recombination in quantum wells. In this letter, we report a study of photocurrent and dark I.V measurements on InAs/x_p1-x/InP$_{p-i}$(MQW)-n structures to emphasize the influence of both electric field and temperature on the absorption/transport properties and their direct impact on the electrical performances. MQW p-i-n samples studied in this work were grown by Chemical Beam Epitaxy (CBE) at 510°C on (100) S-doped InP (001) substrates. Ten periods of not intentionally doped InAsxP1-x/InP MQWs were incorporated in the intrinsic region of InP p-i-n structures for high arsenic composition values (0.26-0.65) and different well/barrier thickness. The structural parameters were obtained by using high-resolution x-ray diffraction analysis and C-V measurements. The analysis of the maximized collection efficiency in the MQW region has been discussed in terms of thermal escape and recombination rates in the wells by evidencing the influence of the InAsxP1-x/InP quantum well composition, thickness and interface quality. The existence of a critical threshold built-in electric field value above which total carrier collection becomes possible is demonstrated. Maximized carrier collection, lower dark current characteristics (two order of magnitude) and high output volt age are systematically reached for built-in electric field exceeding the critical value while similar structures operating with a substantially lower built-in electric field (e.g. identical well characteristics but thicker i region) yields non-optimized collection of carrier in this area, higher dark

current and altered voltage output. The dependence of the maximized carrier absorption and collection in the intrinsic region with the temperature is also reported. The oscillator strength fosc of the fundamental excitonic transition is deduced from the line-shape of photocurrent spectra in the temperature range of 90 to 350K. An enhancement of fosc is evidenced with decreasing temperature providing largest absorption properties in the MQW region. Dark currents are finally found to dramatically decrease at lower temperature, demonstrating a substantial voltage output improvement for MQW-based devices.

10:00 AM Break

10:20 AM
Improved Heterointerface Quality of AlGaAs/GaAs Quantum Wires Characterized by AFM and Microscopic Optical Measurements: *Xue-Lun Wang*[1]; Mutsuo Ogura[1]; Valia Voliotis[2]; Roger Grousson[2]; [1]Electrotechnical Laboratory and CREST, Japan Science and Technology Corporation, 1-1-4 Umezono, Tsukuba, Ibaraki 305 Japan; [2]Groupe de Physique des Solides, CNRS, Universities Paris 6 and Paris 7, 2 place Jussieu, F-75251, Paris Cedex 05 France

Although much progress has been achieved in the fabrication of high-quality quantum wires (QWR) and quantum dots (QD), the heterointerface quality of these structures which influences severely their optical and electronic properties is still much poorer compared with quantum well structure whose heterointerface can be controlled to an atomic level. We have developed a new technique for the growth of high-quality AlGaAs/GaAs QWRs on V-grooved substrate using flow rate modulation. The average interface fluctuation of QWRs grown by this method is found to be only about 1 monolayer (ML) from micro-photoluminescence (micro-PL) characterization. In order to further improve the interface quality, surface roughness on the initial V-grooved GaAs substrate induced during V-groove preparation processes should be reduced. In this paper, we show that this roughness can be reduced greatly just by a simple etching treatment of the V-grooved substrate before growth. The V-grooved GaAs substrates prepared by photolithography and wet chemical etchings were treated with two kinds of processes: a) ultrasonic organic solvent cleaning + native oxide removal by HCl. This is the process we used in our previous works. b) ultrasonic organic solvent cleaning + 10 sec wet chemical etching by NH4OH:H2O2:H2O (1:3:50) solution. We first investigated the surface morphology of the V-grooved substrates by atomic force microscopy (AFM). On the surface of the sample without NH4OH etching, we can observe large terraces of several 100 – 1000 nm long on the (111)A side wall along the [01-1] V-groove direction. Within these large terraces, short range roughness exist, especially on regions where the (001) flat and the (111)A side wall facets intersect. The long and the short range roughness originated from misorientation of the V-groove stripe from the exact [01-1] direction and some size fluctuations of the photoresist edge, respectively. However, on the surface of the sample etched with NH4OH solution, the short-range roughness disappeared almost completely, and the step height between adjacent long-range large terraces was also reduced greatly. The improvement of QWR interface uniformity was clearly revealed by micro-PL measurements. The micro-PL spectrum of a 5 nm thick QWR without NH4OH etching is split into about 10 sharp peaks (linewidth < 0.5 meV) distributed over an energy range of about 10 meV, which can be explained by the formation of 20-100 nm long extended ML islands along the wire direction. However, the micro-PL spectrum of the QWR grown on NH4OH etched substrate is usually composed of two well-resolved peak groups separated by 2-5 meV. Within one peak group, only one or two very sharp peaks (<0.2meV) exist. We attribute each of these peak groups to luminescence from one large terrace. The ML step islands in these large terraces seem to be much longer than those of the sample grown without NH4OH etching. In summary, we have presented a very simple and very effective method for improving the heterointerface quality of quantum nanostructures grown on patterned substrates.

10:40 AM +

Optical Properties in InGaN/GaN Structures Grown by Metal-Organic Chemical Vapor Deposition: *Mee Yi Ryu*[1]; Eun-joo Shin[2]; J. H. Song[1]; S. W. Park[1]; P. W. Yu[1]; N. W. Song[2]; J. I. Lee[2]; D. Kim[2]; E. S. Oh[3]; Y. J. Park[3]; H. S. Park[3]; T. I. Kim[3]; [1]Kwangju Institute of Science and Technology, Dept. of Inform. and Comm., 1 Oryong-dong, Puk-gu, Kwangju 500-712 ROK; [2]Korea Research Institute of Standards and Science, Spectroscopy Group, P.O. Box 102, Taejon 305-600 ROK; [3]Samsung Advanced Institute of Technology, Photonics Laboratory, P.O. Box 111, Suwon 440-600 ROK

We have employed photoluminescence (PL), photoreflectance (PR), and time-resolved photoluminescence (TRPL) measurements to study the mechanisms of optical transitions in InGaN/GaN structures. The sample used in this study was grown on a sapphire substrate by metal-organic chemical vapor deposition. The nominally undoped 22 nm wurtzite $In_xGa_{1-x}N$ epilayer was grown on about 2 mm GaN epilayer and capped with about 0.1 mm GaN epilayer. The $In_xGa_{1-x}N$ layer has about 18 % indium contents (x@0.18) determined by double-crystal x-ray diffraction. Time-correlated single photon counting (TCSPC) system has been employed to study the carrier dynamics of InGaN/GaN structures. The excitation source is a picosecond dual-jet dye laser synchronously pumped by a mode-locked argon ion laser. The instrumental response function (IRF) of our TCSPC system was typically 60 ps. The cw PL measurements were performed using the 325 nm line of a cw He-Cd laser. The probe light used for PR was obtained by passing the Xe-lamp through a 50-cm monochromator. The reflection modulation was achieved by photoexcited electron-hole pair generation using a He-Cd laser chopped at 80 Hz. Figure 1 shows the PL spectra of InGaN/GaN structures measured at 10 K for four different excitation intensities ranging from $I_{exc} = 0.001I_0$ to I_0. As the excitation intensity increases, the PL spectra are broadened asymmetrically and the main peak is shifted toward higher energies. This blueshift may be due to combined effects of band filling of the localized states and Coulomb screening of the quantum confined Stark effect (QCSE) or Franz-Keldysh effect induced by the piezoelectric field. The emission intensity (I_{emi}) of the main peak increases superlinearly with excitation intensity (I_{exc}), following a power-law form, I_{emi} a $I_{exc}^{1.51}$. The superlinear increase of I_{emi} with I_{exc} indicates that the main emission in InGaN/GaN structures is the recombination of localized exciton. Figure 2 shows the PL and PR spectra for InGaN/GaN structures measured at 10 K. The PR spectrum was analyzed by the low-field PR line-shape function, third derivative functional form. The averaged bandgap energy of InGaN layer is 3.053 eV. The PL main peak is located at 2.895 eV. The Stokes-like shift is about 160 meV. In Fig. 3, we plot the recombination lifetimes of InGaN/GaN structures as a function of emission energy. The PL decay kinetics can be fit by two exponential functions. As the emission energy increases, the decay times t_1 and t_2 decrease from 450 ps and 1.89 ns to 110 ps and 0.65 ns, respectively. The recombination lifetimes of the localized excitons decrease with increasing emission energy. Thus the lifetime behaviors of t_1 and t_2 can be explained by the recombination of excitons localized at a certain potential minima.

11:00 AM

Modulation Spectroscopy Study of a Strained Layer GaAs/GaAsP Multiple Quantum Well Structure: *L. Malikova*[1]; Fred H. Pollak[1]; Oleg Gorea[2]; Alexander Korotcov[2]; [1]Brooklyn College of CUNY, Phys. Dept., 3438N, 2900 Bedford Ave., Brooklyn, NY 11210-2889 USA; [2]State University of Moldova, Dept. of Phys., Chisinau, MD 2009 Moldova

Using contactless electroreflectance (CER) and piezoreflectance (PZR) at 300K we have characterized a GaAs/GaAs1-xPx multiple quantum well (MQW) structure grown by chloride transport chemical vapor deposition (CTCVD) on a GaAs (001) substrate. For comparison we have also studied "GaAs"(nominal) and GaAsP epilayers fabricated by this method. From a detailed lineshape fit to the CER data from the epilayers we have determined the energies of the fundamental band gap and hence the phosphorous composition. The nominal "GaAs" epilayers were found to have phosphorous compositions of about 2.5%-3.2%, a result of the phosphorous diffusion between growth chambers in the reactor. The GaAs1-xPx epilayer had x = 0.29. Atomic force microscopy was employed to investigate the surface morphology of (a) the

230 ÿ GaAsP top layer of the MQW in addition to (b) a 2000ÿ GaAsP epilayer. From the absence of any cross-hatch pattern associated with misfit dislocations on the former we concluded that the GaAsP in the MQW is pseudomorphic. On the other hand the 2000ÿ epilayer exhibited signs of strain relaxation. We employed both CER and PZR in order to conclusively identify the nature of the light-hole transitions, an important consideration in determining the band offset. It has been shown that in the PZR spectrum the light-hole transitions are accentuated in relation to CER data. For the GaAs0.97P0.03/GaAs0.71P0.29 MQW, comparison between the experimentally observed energies of a number of quantum transitions with a theoretical envelope function calculation, including the effects of strain in the barriers, made it possible to evaluate the unstrained conduction band offset parameter Qc = 0.50±0.05. Our value for the band offset parameter is discussed in relation to other works.

11:20 AM

The Annealing Effects on Optical and Structural Properties of (ZnSe)2(CdSe)n Short-Period-Superlattices Multiple Quantum Wells: *Ru Chin Tu*[1]; Yan Kuin Su[1]; Shu Tsun Chou[2]; [1]National Cheng-Kung University, Dept. of Elect. Eng., 1, University Rd., Tainan City 703 Taiwan; [2]Chung Cheng Institute of Technology, Dept. of Elect. Eng., Taoyuan 335 Taiwan

This work investigates how thermal annealing affects the optical and structural properties of (ZnSe)2(CdSe)n short-period-superlattices multiple quantum wells (SPS MQW) grown by molecular beam epitaxy using photoluminescence (PL) and high resolution transmission electron microscopy (HRTEM) techniques. Three sets of the MQW samples, denoted as samples A, B, and C, were grown on (100) GaAs substrates by molecular beam epitaxy. Each quantum well in sample A contained eight pairs of (ZnSe)2(CdSe)2 SPS; each well in sample B contained eight pairs of (ZnSe)2(CdSe)1 SPS. The conventional Zn0.5Cd0.5Se/ZnSe MQW in sample C were configured similarly to those in samples A and B, except that Zn0.5Cd0.5Se ternary wells were grown for comparison purposes. After growth, all samples were annealed at temperatures between 350 ¢XC and 475 ¢XC. According to Figs. 1(a) and 1(b), much larger blueshifts were observed from both annealed SPS MQW samples than from the annealed conventional MQW sample. For example, annealing at 4 50 ¢XC for 30 minutes produced blueshifts of 210 meV in sample A, and 90 meV in sample B, but only 20 meV in sample C. Figure 2 shows the PL-peak-energy blueshift as a function of annealing temperature for all samples. According to our experience and previous investigations, the obvious degradation of ZnCdSe quantum wells should not be observed until the annealing temperature rises above 500 ¢XC. Hence, the small blueshift observed in sample C could be attributed to the small interdiffusion along the growth direction, where the interface between ZnCdSe well and ZnSe barrier is located. A characteristic that differentiates annealed SPS MQW from annealed conventional quantum wells is that much greater blueshifts can be observed in annealed SPS MQW as the annealing temperature rises above 400 ¢XC. The cross-sectional TEM images from sample B are shown in Fig. 3. Fig. 3(a) shows the image from the as-grown sample, and Fig. 3(b) shows the image from the same sample after it had been annealed at 450 ¢XC for 3 0 minutes. Figure 3(a) clearly shows SPS structures in the well regions, in contrast to Fig. 3(b), where the SPS structures cannot be clearly seen. This implies that annealing the sample at 450 ¢XC for 30 minutes caused the disappearance of the SPS structures in the well regions. The strong intermixing at such annealing temperatures destroys the SPS structure in the wells, and restores them into the mixed ZnCdSe ternary, thereby making them similar to conventional MQWs. Therefore, this large blueshift could result from thermally induced interdiffusion of Zn and Cd atoms between alternate ZnSe and CdSe layers of SPS structures in the well regions. The magnitude of blueshift depends upon the extent of intermixing between alternate ZnSe and CdSe layers. Therefore, we attribute the larger blueshifts to thermally induced interdiffusion of Zn and Cd atoms between alternate ZnSe and CdSe layers.

11:40 AM +

Transient Luminescence and Exciton Dynamics in (CdMn)Te/(CdMg)Te Quantum Wells: *Mukul C. Debnath*[1]; J. X. Shen[1]; I. Souma[1]; E. Shirado[1]; T. Saito[1]; T. Sato[1]; R. Pittini[1]; Y. Oka[1]; [1]Tohoku University, Research Institute for Scientific Measurements, Katahira 2-1-1, Sendai, Miyagi 980-8577 Japan

The exciton recombination rate determines the high-frequency limit of the operation of electro-optical devices. We determine the exciton recombination time by measuring the lifetime of the PL intensity in the energy range of the excitons. In semimagnetic quantum wells (QWs) like Cd1-xMnxTe/Cd1-xMgxTe, the photoluminescence (PL) decay time of the excitonic signal becomes much longer than in non-magnetic QWs. In these semimagnetic QWs, the decay of the PL intensity is found to follow a double exponential law [1] instead of the simple-exponential law usually assumed for the exciton recombination. Interestingly, we found that the PL intensity with a longer decay time is strongly reduced by applying a magnetic field of the order of 1T. We prepared QWs with different well widths and Mn compositions and we found a correlation between the reduction of the long decay time and the giant Zeeman splitting of the excitons in the semimagnetic wells. From the analysis of the field dependence of the time-resolved PL signal, we attribute the long decay time to the long-living dark excitons (J=2) located energetically lower than the bright excitons (J=1) in zero field [2]. These dark excitons can recombine only after a spin flip process, which turns the dark excitons into bright excitons. In these terms, the difference between the long and the short decay times of the transient PL intensity is determined by the spin-flip processes occurring in the QW. The application of a field raises the energy of the dark excitons over the energy of the bright excitons due to the giant Zeeman splitting. In this case, the dark excitons are depleted and no longer contribute to the PL decay time. Therefore, the long-living PL component is no more observable under magnetic fields. Furthermore, we studied also the tunneling mechanism of both, the bright and the dark excitons in MBE grown Cd1-xMnxTe/Cd1-yMgyTe and CdTe/Cd1-xMnxTe asymmetric double QWs (ADQWs). With a decreasing barrier width, the PL intensity decreases for the narrow wells (NWs) suggesting an exciton tunneling from NWs to the wide wells (WWs). The long-living PL component disappears for the NW of the coupled ADQW with decreasing barrier width. This demonstrates that both dark and bright excitons tunnel from the NW to the WW. Moreover, the transient behavior for the WW is also affected by the decrease of the barrier width. The long-living PL component increases, indicating that more dark excitons tunnel through the barrier. Thus we found that tunneling is a spin conserving process in this material. The long-living PL component is not due to the tunneling of the bright excitons, since such a long-living component can not be found in high fields when the dark excitons are depleted after the energy crossing with the bright excitons. In spite of the exciton tunneling, the dynamics of the excitonic magnetic polaron in ADQW samples with different barrier widths is almost identical as follows from the analysis of the time relaxation of the polaron energy for the WWs. Thus, our experiments suggest that the polaron formation process is not influenced by the tunneling of the excitons between the QWs. References: [1] M. C. Debnath, I. Souma, E. Shirado, T. Sato, J. X. Shen, and Y. Oka, J. Appl. Phys., April, 1999 in press. [2] Al. L. Efros, M. Rosen, M. Kuno, M. Nirmal, D. J. Norris, and M. Bawendi, Phys. Rev. B54, 4843 (1996).

Session Z. Wide Bandgap Nitrides (MBE, Theory, and AlN)

Friday AM   Room: Lotte Lehman Hall
July 2, 1999   Location: Music Building

Session Chairs: Chris van der Walle, Xerox, Palo Alto, CA USA; Russell Dupuis, University of Texas, Austin, TX USA

8:20 AM +

Dielectric and Lattice-Dynamical Properties of III-Nitrides: *Ulrike Grossner*[1]; Jurgen Furthmuller[1]; Friedhelm Bechstedt[1]; [1]Friedrich-Schiller-Universitaet, IFTO, Max-Wien-Platz 1, Jena 07743 Germany

The dielectric and lattice-dynamical properties of BN, AlN, GaN, and InN are calculated using a combination of density functional theory (DFT) within the local density approximation (LDA) and generalized response theory, the density-functional pertubation theory (DFPT)[1]. Up to now, the lattice-dynamical properties of InN were not described reasonably within DFT and DFPT. However, this is possible in the framework of a generalization[2] of the ab-initio force constant method. We follow the line of the papers[2,3,4] in calculating directly the interatomic force constant matrix. The method is rather similar to the frozen-phonon method. It therefore describes the LO modes incorrectly. The long-range electric field is not induced. Kern et al.[2] suggested to determine this field or, more strictly speaking, the screened Born ion charges that generate this field, from an artifact of the periodic boundary conditions. The false electrostatic field occurring in the supercell approach should be compensated to describe reality. With the knowledge of the screened Born charges Z* the nonanalytical long-range electric part of the dynamical matrix[5] is constructed and added to the force constant matrix[2]. We present complete dispersion relations as well as screened charges Z* and the phonon frequencies resulting for the high-symmetry points Gamma, X, and L in the fcc Brillouin zone (BZ). In the case of BN, AlN, and GaN we compare our data with other first-principles calculations using the DFPT[6] and first order Raman data for cubic epitaxial layers[7,8,9]. The agreement of the two different ab initio calculations for the acoustic phonon branches is excellent. The deviations in the frequency region of the optical branches are slightly larger. The main reason is related to the smaller screened effective ion charges Z* in the present calculations. The agreement of the frequencies calculated for Gamma phonons and the first-order Raman data measured for cubic epitaxial layers is also good. The discrepancy in the case of the TO phonons is a result of the overestimation of the corresponding force constant due to the LDA-underestimation of the lattice constant. For InN the first ab initio calculations of phonons are presented. We end up with a TO-phonon frequency of 467 cm-1 at the Gamma point, whereas the experimental value is 457 cm-1[10]. The phonon frequencies are in excellent agreement with other data available in the literature as well as for experimental values. This holds also for the elastic constants which have been derived from the sound velocities. Dispersion relations of 3C-InN. We observe a weakening of the dependence of the short-range elastic force constant on the lattice constant along the nitride row.

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Pressure Coefficient of Nitrides and Their III-V Alloys: *Su-Huai Wei*[1]; T. Mattila[1]; A. Zunger[1]; [1]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

Using first principles LAPW method and empirical pseudopotential method we have studied the pressure coefficients a_p of the direct band gap transition for nitrides in both zinc-blende and wurtzite structure and their III-V alloys. We find that (i) a_p decreases from AlN to GaN to InN. (ii) a_p in the wurtzite structure is only slightly larger than that in the zinc-blend structure, and (iii) the pressure coefficients

of the alloys are much smaller than the composition averaged values of their binary constituents. The large reduction of the pressure coefficients of the alloys are due to charge localization of the band-edge states, which is also responsible for the large band gap bowing in these systems. We find that small amount of nitrogen substitution in GaAs induces a splitting of the L_{1c} state. The induced $a_1(L_{1c})$ state hybridize with $a_1(\Gamma_{1c})$, resulting in the experimentally observed E_- and E_+ states. Under pressure, interaction between the E_- and E_+ states with a_1 symmetry leads to an anti-crossing of E_- and E_+ states, and results in the interchange of their dominant character at high pressures. Our results explains the experimentally observed (a) changes in the pressure coefficients of these states, (b) changes in the transition intensities to valence band, and (c) the absence of the crossing between E_- (CBM) and X_{1c} state [see W. Shan et al., Phys. Rev. Lett. {\bf 82}, 1221 (1999)]. We also shows that the observed near-saturation of the pressure coefficient of the E_- state at high pressures is partially due to alloying effect and partially due to increase of the bulk modulus of the material under pressure. Work is supported by U.S. DOE, contract No. DE-AC02-83-CH10093

9:00 AM
Measurement of Al Mole Fraction of Bulk AlGaN and AlGaN/ GaN Heterostructures by Photoconductance and Reflectance Methods: *L. S. Yu*[1]; D. Qiao[1]; S. S. Lau[1]; J. M. Redwing[2]; [1]University of California, San Diego, Dept. of Elect. and Comp. Eng., 9500 Gilman Dr., La Jolla, CA 92093-0407 USA; [2]ATMI, Epitronics, 21002 North 19 Ave., Suite 5, Phoenix, AZ 85027 USA

The Al mole fraction in the AlGaN layer is an important parameter for the performance of the devices based on AlGaN. The Al fraction can be estimated from the energy bandgap of AlGaN from the following equation: EgAlGaN=EgGaN(1-x)+EgAlNx-bx(1-x), where x is the Al fraction, b the direct gap bowing parameter. Optical methods are commonly used to measure the bandgap of semiconductors, however, the conventional optical absorption method is not suitable for measuring the bandgap of AlGaN grown on SiC substrate or AlGaN/GaN heterostructures since the energy bandgap of AlGaN is larger than that of SiC and GaN. For the photoluminescence method, special UV lasers with large photon energy are needed when the Al fraction is relatively high. We report here two simple optical methods to measure the bandgap of both the bulk AlGaN and AlGaN/GaN heterostructures, i.e., the photoconductance and the optical reflectance methods. In the photoconductance method, the bandgap is determined by the sharp increase of photocurrent when the photon energy of the incident light reaches the bandgap of AlGaN. For bulk AlGaN samples, the photocurrent was measured by a setup consisting a halogen light source, an optical beam chopper, a monochromator and a lock-in amplifier. With the light source used in our experiment, the maximum Al fraction that can be measured is about 0.23 (bandgap @ 3.89 eV). If a Xe lamp instead of the halogen lamp is used, the Al fraction up to 0.5 can be measured. For the AlGaN/GaN heterostructures, a special DC method was developed to avoid the persistent photoconductivity in the 2D electron gas channel of the heterostructure samples. In the optical reflectance method, the bandgap is estimated by the change of the reflectance when the photon energy of the incident light exceeds the bandgap of AlGaN. The experimental results obtained by these methods were consistent with the results obtained by the photoluminescence measurements. The merits and the accuracy of these methods will be discussed.

9:20 AM +
Growth of Bulk ALN by Physical Vapor Transport: *Tim Housain*[1]; P. Zhou[1]; H. N. Jayatirtha[1]; M. G. Spencer[1]; V. Dmitriev[2]; Yu Melnik[2]; A. Nikolaev[3]; [1]Howard Univeristy School of Engineering, Rm. 1124 Mat. Sci. Center, 2300 6th St. NW, Washington, DC 20059 USA; [2]TDI INC., 8660 Dakota Dr., Gaithersburg, MD 20877 USA; [3]A.F. Ioffe Institute, 26 Polytechnicheskaya St., St. Petersburg, Russia

Nitride based materials have garnered a great deal of interest for microwave, power and opto-electronic applications. A major issue in the development of this technology is the choice of substrate. Due to the extremely high vapor pressure of nitrogen over Gallium Nitride (GaN), pure GaN substrates are very difficult to produce and currently almost all nitride-based devices are fabricated by hetero-epitaxy on

either Sapphire or Silicon Carbide (SiC). Another substrate alternative is Aluminum Nitride (AlN). AlN has a significantly lower vapor pressure of nitrogen and can be grown in bulk form. In this presentation we report on our results in the growth of AlN by physical vapor transport. AlN was grown by the decomposition of AlN powder in the presence of a nitrogen ambient. The growth of AlN was investigated in the temperature range of 2000-2300°C with nitrogen pressures of 100-600 Torr. The separation between the seed and AlN powder was in the range of 4mm under a temperature gradient of 1-3oC/mm. Under these conditions the growth rate varied between 10 and 50 microns/hr. Several different seed crystals were investigated, singular 6H-SiC, 3.5o off-axis 6H-SiC and 8o off-axis 4H-SiC, and AlN grown by hydride vapor deposition. Auger electron microscopy, Atomic Force Microscopy (AFM) and various X-ray diffraction techniques were used to investigate the AlN. Transmission electron microscopy (TEM) of this material is in progress. Auger and X-ray results indicated that under certain conditions a solid solution of SiC and AlN is formed. Under AFM examination three dimensional spiral growth was observed on the on-axis material while step like growth was observed on the off-axis material. Additionally, cracking of the AlN was observed when the growth was performed on SiC substrates. We believe that this cracking is due the difference in the thermal coefficients of expansion for SiC and AlN. Growth on the AlN seeds did not produce cracking of the material. Details of these results will be presented.

9:40 AM
Microstructural Analysis of the Recrystallization in AlN Nucleation Layers: *Yves-Matthieu Le Vaillant*[1]; René Bisaro[2]; Jean Olivier[2]; Pierre Galtier[2]; Jean-Yves Duboz[2]; Bernard Gil[3]; Sandra Ruffenach-Clur[3]; Olivier Briot[3]; Roger-Louis Aulombard[3]; [1]Thomson-CSF/University Montpellier, Laboratoire Central de Recherches/GES, Universit? de Montpellier II, pl. E. Bataillon, GES, cc074, Montpellier 34095 France; [2]Thomson-CSF, Laboratoire Central de Recherches, Domaine de Corbeville, Orsay 91 404 France; [3]Université de Montpellier, Groupe d'Etude des Semiconducteurs, pl. E. Bataillon, Montpellier 34095 France

The optimization of the nucleation layer is a key-point in the growth of nitride materials. This thin AlN (or GaN) layer is generally epitaxied at a low temperature, then subjected to an annealing before the deposition of the main epilayer. We studied the recrystallization mechanisms during this annealing in AlN nucleation layers (~500 nm thick) epitaxied by MOCVD method on [0001]-oriented sapphire substrates. A morphological and structural characterization was obtained by x-ray diffraction, transmission electron microscopy (TEM), and atomic force microscopy (AFM). The x-ray diffraction analysis is based on a special Fourier transform, where instead of considering the crystal as diffracting planes, this one must be thought in term of diffracting columns. This approach is known as the Warren-Averbach method. The choice of such a Fourier real space gives much information on partially crystallized solids. The length of diffracting columns is related to the size of the crystallites. The distortion of the columns gives access to the stress. With this precise and statistical method, we obtain distributions in size and stress for two annealing temperatures (980°C and 1070°C), at various annealing time (from 0 to 15 min). TEM observations confirm the previous analysis, giving more details on the shape of the crystallized domains. Their angular orientation distribution is provided by x-ray rocking-curves. In the bulk of the material, an Ostwald ripening (or secondary recrystallization) is pointed out by the emergence of big crystallites while the smaller ones are consumed. After nucleation and grain growth, this stage of recrystallization corresponds to an instability in the growth rate of the crystallites. The driving force of the ripening is the lessening of the total interface between the amorphous matrice and crystals. The kinetics of precipitation is interpreted using the theoretical model of Lifshitz and Slyozov. Based on the local concentration of each element (here Al and N), this model takes into account the influence of the strain induced by the phase transformation. At the surface of the layer, a similar phenomenon is observed. AFM reveals the change of the surface morphology. During thermal annealing, some of the grains firstly grow vertically, increasing the roughness. Then, when the annealing time reaches 5 minutes, a coalescence of the grains leads to a smooth surface. Empirical studies show that an optimized nucleation layer, according to the quality of the main GaN epilayer, is incompletely recrystallized.

The role of the nucleation layer is to enhance a pseudo bidimensionnal growth of the main epilayer. We give some hypothesis on the improvement of this heteroepitaxy.

10:00 AM Break

10:20 AM
Lateral Epitaxial Overgrowth of GaN Films by Molecular Beam Epitaxy: *M. R. Hoit*[1]; A. M. Dabiran[2]; B. E. Ishaug[1]; A. Parkhomovsky[1]; R. Held[1]; P. I. Cohen[1]; [1]University of Minnesota, Elect. and Comp. Eng., 200 Union St. SE, Minneapolis, MN 55455 USA; [2]Silver Sky Technologies, Inc., 644 Pond View Terrace, St. Paul, MN 55120 USA

Lateral epitaxial overgrowth (LEO) of GaN provides films with reduced defect density, better electrical and optical properties, and substantial improvements in device performance. All of the reported work on this technique to date have been based on material overgrown using MOCVD on patterned masks. In this investigation, we have used molecular beam epitaxy (MBE) and demonstrate LEO of GaN directly on sapphire. The growth proceeds from the sidewalls of features etched in thin GaN films. A mask was placed on a thin (~15 nm) GaN film grown by MBE on a sapphire substrate. The pattern consisted of 1 mm by 2 mm rectangular regions of 1.5 micron spaced, 2 micron wide lines and of pinwheels with 4 and 6 micron wide and 100 micron long lines every 15 degrees. The pattern was etched through the thin GaN down to the sapphire substrate using a chlorine/argon chemistry in an RF reactive ion etcher. Before starting the overgrowth, the exposed sapphire surface was etched with a standard sapphire etch which does not attack the patterned GaN. An approximately 300 nm thick GaN film, as measured by AFM, was grown on the patterned GaN surface. The growth was carried out under a Ga-rich conditions and at a temperature well above the condensation temperature of Ga on GaN as determined by desorption mass spectroscopy (DMS). In this growth regime no new GaN nucleation occurs on the exposed sapphire regions. Instead, highly mobile Ga adatoms diffuse to and are incorporated at the sidewalls of the patterned GaN film resulting in LEO growth. The LEO layer grown in this way was characterized using atomic force microscopy (AFM), scanning electron microscopy (SEM), and spatially resolved cathodoluminescence (CL). AFM and SEM results showed a anisotropic lateral to vertical growth ratio of about 3:1 in the optimum lateral growth direction. Also, an improvement in the optical quality of the LEO material was shown by the enhancement of band-edge emission, and a reduction of yellow-green emission. AFM and SEM images of the pinwheel pattern regions also indicated no nucleation of GaN on the exposed sapphire regions. This work is partially supported by BMDO SBIR N00014-98-M-0119 administered by the ONR.

10:40 AM
Strain Relaxation and Homogeneity of AlGaN Grown by Molecular Beam Epitaxy: *Sven Einfeldt*[1]; Kai Vogeler[1]; Verena Kirchner[1]; Tim Boettcher[1]; Heidrun Heinke[1]; Detlef Hommel[1]; Dirk Rudloff[2]; Juergen Christen[2]; [1]University of Bremen, Institute of Solid State Phys., P.O. Box 330440, Bremen 28334 Germany; [2]University of Magdeburg, Institute of Experimental Phys., P.O. Box 4120, Magdeburg 39016 Germany

Thick AlGaN layers are an important component in many opto-electronic and electronic devices based on group III nitrides. Besides the dopability of this ternary alloy, the generation of extended defects namely film cracks seriously limits the possible layout of layer structures for device applications. This issue as well as the compositional homogeneity of AlGaN are investigated in this paper using molecular beam epitaxy (MBE) for the growth of $Al(x)Ga(1-x)N$ (1 μm)/GaN (1 μm) heterostructures on c-plane sapphire. The results are discussed with respect to InGaN as the other ternary material in nitride devices. The growth of pseudomorphic $Al(x)Ga(1-x)N$ layers on GaN is limited by the generation of dislocations or film cracks releasing the tensile elastic strain. Relaxation mechanisms are studied with respect to the aluminum content as well as to the perfection of the GaN layer, which was varied due to its growth temperature in MBE or by the use of GaN layers grown by metalorganic vapour phase epitaxy (MOVPE). The critical aluminum content for visible crack formation in the 1 μm thick layers is found to be 0.08 for the growth on MOVPE layers but 0.10 for the growth on MBE layers. The crack density increases with the alumi-

num content and is more pronounced for the growth on the MOVPE GaN. Simultaneously with the occurrence of cracks the strain parameter measured by X-ray diffraction becomes smaller than one. The compositional homogeneity was investigated by spatially resolved cathodoluminescence performed at low temperatures. Spatially integrated spectra are found to consist of two or three peaks. The higher-energetic peak, which is believed to result from the donor bound exciton, evolves with a bowing parameter of 0.3 eV for aluminum contents below 0.2 assuming a peak energy of 5.8 eV for AlN. The dominant lower-energetic peak corresponds to the well-known 3.41 eV line in GaN often attributed to extended defects. All spatially resolved local spectra of a certain sample show peaks at nearly the same spectral positions. Histograms of the wavelength variation of the dominant peak in the local spectra are used for an upper estimation of compositional fluctuations. The half width of the histogram peak is found to linearly increase with the mean aluminum content, corresponding to an absolute variation of the aluminum content of only 0.002 for x = 0.20.

11:00 AM +
Surfactant Effect and Polarity Inversion Due to Mg on the Ga-N(0001) Surface: *V. Ramachandran*[1]; R. M. Feenstra[1]; D. W. Greve[2]; J. E. Northrup[3]; [1]Carnegie Mellon University, Dept. of Phys., Pittsburgh, PA 15213 USA; [2]Carnegie Mellon University, Dept. of Elect. and Comp. Eng., Pittsburgh, PA 15213 USA; [3]Xerox, Palo Alto Research Center, 3333 Coyote Hill Rd., Palo Alto, CA 94304 USA

Submonolayer quantities of Mg deposited during the growth of GaN films on 6H-SiC(0001) by molecular beam epitaxy (MBE) are seen to dramatically stabilize film growth in the Ga-poor growth regime. In the absence of Mg, GaN growth in this regime is characterized by 3-dimensional growth as evidenced by spotty reflection high-energy electron diffraction (RHEED) patterns, whereas growth in the Ga-rich regime consistently shows streaky, 1x1 RHEED patterns. In our experiments, MBE growth of GaN is performed under successively reduced Ga fluxes. In the Ga-poor regime, exposure of the growing surface to <0.2 monolayer (ML) of Mg causes the RHEED pattern to change from spotty to streaky 1x1, clearly indicative of the surfactant effect of Mg. This effect is observed at least until the Ga flux is reduced to about half that required to maintain Ga-rich conditions at the clean GaN surface. Under more Ga-poor conditions obtained by increasing the nitrogen pressure, the RHEED pattern changes to a streaky 2x2 which is maintained during the growth. We propose that Mg present on the GaN surface increases the mobility of Ga on N-rich surfaces leading to a return to 2-D growth upon Mg exposure in the Ga-poor regime. Deposition of larger quantities, approximately 1 ML, of Mg on Ga-polar GaN films (polarity established by substrate - Si-polar SiC, and verified by observations of surface reconstructions) during growth, is found to produce polarity inversion of the entire film. This has been verified by both scanning tunneling microscopy (STM) and RHEED observations of the surface reconstructions after growth is complete. Large scale morphology is similar in both the non-inverted (Ga-polar) and inverted (N-polar) cases, indicating that the polarity inversion is not concomitant with a change in growth mode. Theoretical models for this inversion are under investigation. In particular, a c-plane inversion domain boundary is found to be structurally feasible, and is consistent with the experimental data. This work has been funded by the Office of Naval Research and the National Sci. Foundation.

11:20 AM
Influence of Structural Defects on Transport Properties of GaN Grown by Reactive MBE and Magnetron Sputter Epitaxy (MSE): *Haipeng Tang*[1]; James B. Webb[1]; Jennifer Bardwell[1]; Brian Leathem[1]; Sylvain Charbonneau[1]; Sylvain Raymond[1]; [1]National Research Council, Institute for Microstructural Sciences, Bldg. M-50, Montreal Rd., Ottawa, Ontario K1A 0R6 Canada

GaN layers have been grown using a system equipped for both reactive MBE and MSE (magnetron sputter epitaxy) techniques. The layers grown by the two different methods are plausibly of similar purity, since they had been grown in the same reactor and using the same source materials. However, the MSE grown layers had a significantly poorer crystalline quality compared to those grown by MBE. The FWHM values of the (0002) X-ray rocking curve for the MSE samples are from 600 to 1000 arc-sec, compared with values between 250 and 350 arc-

sec for the MBE samples. The different levels of crystalline imperfection are found to have a profound influence on their doping characteristics and carrier mobility. The mobilities of Si-doped GaN layers grown by MSE show an increase with increasing carrier density (n), to about 80 cm^2/Vs at an n of 1e19 cm^-3. In the low carrier density end (1e17<n<1e18), mobilities fall rapidly, with values of 0.1 to 10 cm^2/Vs. Clearly, ionized impurity scattering does not describe this behavior. Scattering by charged dislocations is proposed to be the dominant scattering mechanism in these films. Carrier trapping at acceptor-like trap sites at the dislocations may also explain a phenomenon that MSE grown GaN layers without intentional doping are always highly resistive and show no autodoping conductivity. In contrast, for the GaN layers grown by reactive MBE, the mobility vs. carrier density curve follows nicely the trend predicted by the ionized impurity scattering mechanism. The mobilities show a peak value of 560 cm^2/Vs at n=1e17 cm^-3, and decrease with increasing n, to about 180 cm^2/Vs at 1e19 cm^-3. The peak mobility value is among the highest values ever reported for GaN grown by MBE, which reaffirms the high purity of our growth system. The higher crystalline quality of the MBE grown layers resulted in dramatic reduction in the number of carrier traps and their importance in carrier scattering. Their influence, however, is still visible at very low carrier density (<5e16 cm^-3) where mobility begins to drop. In another indication of the low trap density, the MBE layers generally show an autodoping level of 1e16 to 2e17 cm^-3. PL spectra of the MSE samples reveal a broad band centered at 670 nm in addition to the well-known yellow band at 550 nm. The importance of this band relative to the yellow band is temperature dependent, and is less prominent in those samples with smaller x-ray FWHMs. In the high quality MBE samples, this band is not detectable, and the yellow band is also absent or very weak. A possible link between this luminescence band, the yellow band and the mobility affecting trap levels at the charged dislocations is discussed.

11:40 AM +
Optimization of High Quality GaN by MBE: *B. Heying*[1]; I. Smorchkova[2]; C. Elsass[1]; E. Haus[1]; P. Fini[1]; T. Mates[1]; S. P. DenBaars[1]; U. Mishra[2]; J. S. Speck[1]; [1]UC Santa Barbara, Mats. Dept, Santa Barbara, CA 93106 USA; [2]UC Santa Barbara, ECE Dept, Santa Barbara, CA 93109 USA

The carrier concentrations and oxygen impurity levels of MBE-grown GaN films were investigated as a function of substrate temperature and power of the EPI UNI-Bulb rf-plasma nitrogen source. The MBE-GaN films were grown under Ga-stable conditions on GaN template layers grown by metalorganic chemical vapor deposition (MOCVD). The carrier concentrations of the nominally un-doped MBE-GaN films measured from capacitance-voltage (C-V) profiles were found to decrease from 2e18cm-3 to 6e17cm-3 by increasing the substrate temperature used during film growth from 565°C to 680°C at a constant rf-plasma power of 390W. Relative oxygen impurity levels measured from SIMS depth profiles of the GaN films were also found to decrease by 55% for the same temperature increase. The carrier concentrations of MBE-GaN films were also found to decrease from 6e17cm-3 to 8e16cm-3 by decreasing the rf-plasma power from 390W to 150W at a constant substrate temperature of 680°C. The change in rf-plasma power from 390 to 150W had the additional effect of reducing the growth rate from 0.4μm/hour to 0.2μm/hour. SIMS profiles for films grown under the two different rf-plasma powers showed no difference in oxygen impurity levels. However the oxygen levels for both films were at the oxygen detection limit of the SIMS. To further investigate these trends in carrier concentration and oxygen incorporation, an MBE-GaN film was grown with a substrate temperature of 680°C and an rf-plasma power of 150W on top of another MBE-GaN film grown with a substrate temperature of 740°C and an rf-plasma power of 90W. The carrier concentration was found to decrease from to ~1e17cm-3 in the high power, low temperature film to 3e16cm-3 in the low power, high temperature film. The SIMS depth profile also showed a 22% decrease in the oxygen impurity level from the high power, low temperature film to the low power, high temperature film. In the carrier concentration range of ~1e17cm-3 to ~1e18cm-3, oxygen is the dominant source of unintentional carriers. In the range of ~1e16cm-3 to ~1e17cm-3, oxygen also appears to be an important source of carriers,

but the contributions from other impurities, such as nitrogen vacancies, may also be important. Oxygen incorporation is clearly dependent on substrate temperature. Increasing substrate temperature decreases the oxygen sticking coefficient thereby lowering its incorporation. It is unclear what caused the decrease in carrier concentration with the reduction in rf-plasma power. The decrease in unintentional carriers could be due to an unobserved change in the oxygen level (due to the SIMS detection limit), a reduction in the ion damage from the rf-plasma source, or the reduction in growth rate.

Session AA. Metal Contacts to Wide Band Gap Semiconductors

Friday AM   Room: Multicultural Center Theater
July 2, 1999   Location: University Center

Session Chairs: Suzanne Mohney, Penn State University, University Park, PA USA; Lisa Porter, Carnegie Mellon University, Dept. of Mats. Sci. & Eng., Pittsburgh, PA USA; Louis Guido, Carnegie Mellon University, Dept. of Mats. Sci. & Eng., Pittsburgh, PA USA

8:20 AM
Large Schottky Barriers and Memory Operation for Ni/p-GaN Contacts: *Kenji Shiojima*[1]; Tomoya Sugahara[2]; Shiro Sakai[2]; [1]NTT, Photonics Laboratories, 3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-0198 Japan; [2]Tokushima University, Dept. of Elect. and Electr. Eng., 2-1 Minami-josanjima, Tokushima, Tokushima 770-8506 Japan

Large Schottky barriers and memory operation for Ni contacts formed on low Mg-doped p-GaN are reported. For p-GaN, the much higher Schottky barrier height (SBH) (above 2 eV) is expected since the sum of SBH of n and p types (SBH of n-type ~ 1 eV) adds up to the band gap of 3.4 eV. However, the contacts tend to exhibit very leaky Schottky characteristics. Consequently, the mechanism of current flow through the interface has not been established and the exact value of SBH has not yet been estimated. In this study, for the improvement of the leaky characteristics, low Mg doping is examined as a way to improve the surface morphology and widen the depression layer width (W) of the Schottky contacts in order to suppress the tunneling current through the barrier. The 2-mm-thick GaN films were grown on (0001) sapphire using metalorganic chemical vapor deposition (MOCVD). A mixture of Bis-cyclopentadienyl magnesium (CP_2Mg) in H_2 was the Mg precursor. The films were grown at 1075°C with 25-nm-thick low-temperature (T_G=450°C) unintentionally doped GaN buffer layers. The Mg concentration was 1.3×10^{18} cm^-3 according to secondary ion mass spectrometry measurements and the carrier concentration was estimated from capacitance-voltage measurements to be 4×10^{16} cm^-3. A reasonable value of activation efficiency of 3 % can be estimated. After buffered hydrofluoric acid treatment, Ni (100- nm thick) was deposited by electron-beam evaporation. In atomic force microscopy (AFM) observations, the many steps observed confirm the surface of p-GaN is atomically flat. The dislocation density (D_{dis}) is as low as 5.5×10^8 cm^-2, compared with n-GaN, for example, whose D_{dis} is 9×10^8 cm^-2 with a mobility of 330 cm^2/Vs and free electron concentration of 5×10^{17} cm^-3. The contacts show Schottky behavior in current-voltage (I-V) characteristics. Linear regions of more than two orders are seen in the forward semi-log I-V curves, and the reverse current is 1 pA at 10 V. The Schottky barrier is as high as 2.4±0.2 eV and the n value is 1.84±0.06. Our results are in good agreement with the prediction that the sum of the SBH of n and p types adds up to the band gap, as the reported values of Schottky barriers of Ni/n-GaN are around 1 eV. As a result of obtain-

ing the large SBH, carrier capture and emission processes of deep levels in a depletion layer can be observed. The W can be varied by light irradiation or forward current injection to the interface. After the irradiation, because the deep levels are fully negatively ionized, W is small and the apparent SBH is low (~0.8 eV) due to the tunneling. After the injection, the deep levels become neutral, W is large and the original large SBH is seen. These processes are repeatable. Since the time constant is very long, roughly estimated to be 50 days, this contact could be utilized as a memory device.

8:40 AM +

High Temperature Behavior of Barrier Height and Ideality Factor of Ni/Au Contacts to p-type GaN: *Ricky Wenkuei Chuang*[1]; Albert Q. Zou[1]; Jeffrey D. Nay[1]; YongSheng Zhao[1]; Henry P. Lee[1]; Z. J. Dong[2]; F. F. Xiong[2]; Robert Shih[2]; M. Bremser[3]; [1]University of California, Irvine, Dept. of Elect. and Comp. Eng., 3333 Eng. Gateway Westwing, Irvine, CA 92697 USA; [2]Alpha Photonics Inc., 2019 Saturn St., Monterey Park, CA 91754 USA; [3]AIXTRON Inc., 1670 Barclay Blvd., Buffalo Grove, IL 60089 USA

High contact resistance on p-type GaN remains a fundamental technological challenge to be overcome for GaN-based light emitting devices. Despite recent progress using combination of transition metals of Ta and Ti to Dr. hydrogen atoms away from Mg dopants under high temperature (800°Celsius) treatment, which results in record low specific contact resistance (as low as $3x10^{-5}$ W-cm^2) [4], Ni/Au remains the standard p-type contacts used in most LEDs and laser diodes. Furthermore, it is known that thermal annealing reduces the specific contact resistance (Fig. 1(a); see attachment) [1,2]. The reason for the reduction of contact resistance is believed due to removal of contaminants at the metal/semiconductor interface [3]. Despite the effectiveness of thermal annealing in reducing the contact resistance for Ni/Au and other contact metals, no systematic quantitative characterization in terms of electrical and transport parameters such as barrier height or ideality factor modification have been reported. In this paper, we investigate the changes in barrier heights (f_B and ideality factors (n) of Ni/Au contacts on p-GaN as a result of thermal annealing from I-V measurements conducted in the range of 25-300°C. The samples used in the studies were InGaN/GaN single quantum well LED structures with 0.5 microns thick Mg-doped p-GaN cap layer grown by MOVPE. The hole concentration were measured in the range of $\sim$1-3x10^{17} cm^{-3}. Circular contacts surrounded by large area contact pad (Fig. 2(a); see attachment) with separation of 5 and 10 microns were formed by e-beam evaporation of Ni/Au (20 nm/120 nm). Each set of samples containing 4 circular contacts was annealed at 500 and 700°C for 100s in a rapid thermal annealing furnace. Barrier height and the ideality factor were extracted from I-V measurements between the circular contacts and surrounding pad under reverse bias condition between 0 and -0.5 V (relative to the circular pad) and fitting with thermionic transport model (Fig. 1(b); see attachment). Upon annealing at 500°C, the barrier height changes from 0.60 eV to 0.51 eV, with the ideality factor changes from 1.21 to 1.11, as compared to the as-deposited contacts. Further annealing at 700°C, however, results in only minor changes on barrier height (~0.50 eV) and ideality factor (~1.13). Thus, the barrier heights extracted appeared to be saturated at 700°C and above. The results strongly support earlier structural characterization that the removal of interfacial contaminants is responsible for barrier lowering [5]. Based on the measured barrier lowering, the average thickness of the contamination layer is ~0.6 to 1 nm, if we assume the contaminant forms an insulating layer between metal and semiconductor. The results of barrier heights and ideality factors extracted are summarized in Table 1 (attachment). At high measurement temperature, the I-V on all samples become more linear as a result of an increase in carrier concentration and lowering of effective barrier height is noted for all samples, as shown in Fig.2(b) (attachment). The barrier height and ideality factor results are summarized in Table 2 (attachment). In addition to thick Ni/Au layer described above, experiments are underway to determining the thermal annealing on ultra-thin semi-transparent Ni/Au (4nm/4nm) layers employed as current spreading layer for GaN-based LED. Reference: 1. A. Q. Zou, R. W. Chuang, H. P. Lee, Z. J. Dong, F. F. Xiong, and R. Shih, Student Symposium, Southern CA Chapter of AVS, Sept.23, 1998. 2. R. W. Chuang, A. Q. Zou, H. P. Lee, Z. J. Dong, F. F. Xiong, R. Shih, M. Bremser, and H. Juergensen,

presented at 1998 Fall MRS Proceeding and MRS Internet J. Nitride Semicond. Res. 4S1, G6.42, 1999. 3. Masaaki Suzuki, et al, Appl. Phys. Lett., Vol. 74, 275, 1999. 4. T. Mori, et al, Appl. Phys. Lett., Vol. 69, 3537, 1996.5. H. Ishikawa et al, J. Appl. Phys., Vol. 81, 1315, 1997.

9:00 AM

Current Transport Mechanism of Low-Resistance TaTi Ohmic Contact Materials for p-GaN: *Yasuo Koide*[1]; M. Suzuki[1]; T. Arai[1]; Y. Matsunaga[1]; T. Kawakami[1]; Masanori Murakami[1]; T. Uemura[2]; N. Shibata[2]; Y. Taga[3]; [1]Kyoto University, Dept. of Mats. Sci. and Eng., Sakyo-ku, Kyoto 606-8501 Japan; [2]Toyoda Gosei Co. Ltd, Optelectronis, Technical Dept. No.2, Heiwa-cho, Nakashima-gun, Aichi 490-1312 Japan; [3]Toyota Central Research & Development Labs. Inc., Nagakute, Aichi 048-1192 Japan

III-Nitrides semiconductors are a primary candidate for blue or ultraviolet LDs. One of materials-related concerns 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 to improve the performance and reliability of the III-Nitrides LDs, no success has been reported. Recently, we demonstrated a possibility to prepare Ohmic contact materials with specific contact resistances (r_c) lower than 10^{-4} W-cm^2 by the conventional deposition and annealing technique [1]. Although this contact had resistance low enough to manufacture blue LDs, a key issue was deterioration of the r_c values during room-temperature storage. The purpose of the present paper is to understand formation and deterioration mechanisms of the TaTi Ohmic contacts for p-GaN. Transition metals of Ta and Ti, in addition to binary TaTi metals, were used, because these metals were expected to facilitate out-diffusion of hydrogen atoms from a GaN epilayer and increase the ionization efficiency of the Mg atoms in the p-GaN epilayer by removing hydrogen atoms at elevated temperatures. Undoped GaN and Mg-doped p-GaN epilayers were successively grown by MOVPE on sapphire substrates using a thin AlN buffer layer. The hole concentrations of the p-GaN epilayers were 6-7x10^{17} cm^{-3}. Ta and Ti were deposited in an electron beam evaporator. Thickness of a single layered Ta or Ti contact was 50 nm, and the bilayered Ta/Ti contacts with various layer thickness combinations were prepared. Annealing of the samples at temperatures below 800°C was carried out in a vacuum. The electrical properties of these contacts were measured using an I-V method and a circular transmission line method at room-temperature before and after annealing. The microstructural analysis at the p-GaN/TaTi interfaces after annealing at temperature of 800°C for 20 min did not detect a heterostructural intermediate semiconductor layer at the p-GaN/metal interface. From SIMS analysis, the reason for reduction of the r_c values was believed to be due to formation of the p-GaN epilayer with high hole concentration close to the p-GaN/metal interface, caused by removal of hydrogen atoms which bonded with Mg atoms. It was also believed that the reason for deterioration of the r_c values was due to passivation of the Mg acceptors by hydrogen atoms. [1] M. Suzuki, T. Kawakami, T. Arai, S. Kobayashi, Y. Koide, T. Uemura, N. Shibata, and M. Murakami, Appl. Phys. Lett., 74, 275 (1999).

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Indium Tin Oxide as a Transparent Contact to p-GaN: Tal Margalith[1]; *Oded Buchinsky*[2]; Dan A. Cohen[2]; Amber C. Abare[2]; Monica Hansen[1]; Steven P. DenBaars[1]; Larry A. Coldren[2]; [1]University of California at Santa Barbara, Dept. of Mats., Santa Barbara, CA 93106 USA; [2]University of California at Santa Barbara, Dept. of ECE, Santa Barbara, CA 93106 USA

Recently, GaN-based edge-emitting blue lasers have become commercially available. Vertical cavity surface emitting lasers (VCSELs) can be more attractive, especially if arrays are desired. In the absence of conductive mirrors, there is a need for intracavity contacts with good lateral conductivity. The poor conductivity of p-GaN is a major obstacle for VCSELs, so we have investigated indium tin oxide (ITO) as a current spreading transparent contact. The epitaxial structures were grown by MOCVD on sapphire substrates, consisting of 3 mm thick GaN:Si, 5 quantum wells with 3.5 nm thick In$_{0.14}$Ga$_{0.86}$N wells and 5 nm thick In$_{0.04}$Ga$_{0.96}$N:Si barriers, and 180-250 nm thick GaN:Mg. The ITO was deposited in a DC ring magnetron sputtering system, using an ITO target, in an argon/oxygen plasma, and was rapid thermal annealed for

2 minutes in a nitrogen ambient at 600°C, which was the optimal annealing temperature. To demonstrate hole injection and current spreading, broad area and 20 μm diameter LEDs, with either ITO (25 nm) or Ti/Au (5/6 nm) as the p-contacts were fabricated. A metal pad was deposited around the contact layer of the small aperture LEDs. The turn-on voltage of the ITO-contacted broad-area LEDs was around 6 V, a 2 volt increase from metal-contacted devices. The 20 μm diameter devices turned on around 7.5 V. 20 μm aperture ITO-contacted devices on a different wafer (with 180 nm thick p-GaN,) exhibited higher turn-on voltage (10 V). On these devices, a uniform blue luminescence (with peak wavelength of 420 nm and linewidth of 20 nm) was observed from underneath the ITO, indicating effective current spreading from the ring contact to the center of the ITO window. It is suggested that the aforementioned variations in the turn-on voltage are related either to low-level or non-uniform p-doping of the GaN, partial deactivation of the doping at the surface, or formation of a thin gallium oxide layer during the ITO sputtering. Optical transmission and reflection were measured on 25 nm ITO and 5/6 nm Ni/Au film. The optical loss was estimated from the sum of the measured transmission and reflection, R+T. At 420 nm, R+T was 99% for the ITO (corresponding to a power absorption coefficient, a, of 3800 cm^{-1}), while the metal film exhibited R+T=65% (a=3x105 cm^{-1}). More reliable ellipsometry measurements of the ITO resulted in a=664 cm^{-1} (R+T=99.8%). This low absorption, while providing current spreading, suggests the use of ITO as a promising VCSEL intracavity contact.

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Surface Treatment of p-GaN by KOH Solution Studied by Synchrotron Radiation Core-Level Spectroscopy: *Jingxi Sun*[1]; K. A. Rickert[2]; J. M. Redwing[3]; A. B. Ellis[2]; F. J. Himpsel[4]; T. F. Kuech[1]; [1]University of Wisconsin-Madison, Dept. of Chem. Eng., 1415 Eng. Dr., Madison, WI 53706 USA; [2]University of Wisconsin-Madison, Chem. Dept.; [3]Epitronics, Phoenix, AZ; [4]University of Wisconsin-Madison, Phys. Dept., Madison, WI 53706 USA

A low resistance ohmic contact is essential for improving the electrical and optical performance of GaN-based devices. For n-type GaN, a low resistance ohmic contact has been successfully developed. However, low resistance ohmic contacts to p-GaN have been problematic. Recently, it has been reported that the lowest contact resistivity has been achieved by the surface treatment of p-type GaN using a KOH solution prior to metal deposition. The mechanism of this surface treatment has not been systematically investigated. In the present study, we present results of our study of the KOH-based surface treatment of p-GaN using synchrotron-based core-level photoemission and photoabsorption spectroscopy. The chemical bonding at the surface, the chemical identity of the surface species and the shift in the p-GaN surface Fermi level with chemical treatment can be identified in an effort to determine the mechanism underlying this improved contact behavior. The Mg-doped p-GaN films used in this study were grown by metal organic vapor phase epitaxy (MOVPE) on (0001) sapphire substrates. The GaN surface was treated in boiling KOH solution for ~ 10 seconds. C 1s and O1s photoabsorption spectroscopy was used to determine the residual carbon and oxygen on this treated surface. In addition, we used Ga 3d and N 1s core-level photoelectron spectroscopy to detect the chemical bonding states at the surface by determining the chemical shift of the core level energy. The Ga 3d spectra also allow us to determine the position of the GaN surface Fermi level position relative to the gap, which is critical for the electrical behavior of subsequent contacts. It was determined before and after KOH treatment. Our results indicate that the KOH-based treatment alters the p-GaN surface composition. KOH-based treatment can greatly reduce the concentration of N on the surface as well as the C and O-containing contamination. The chemical binding states for both N and Ga are modified after treatment. The Ga-oxide related peak is substantially reduced as is the surface-based N 1s peak after the treatment. The surface Fermi level is shifted from mid band gap toward valence band edge after KOH-based treatment. The modification of the surface composition, and hence the surface chemical bonding states due to the KOH-based treatment contribute to the improvement of surface electronic properties. The low ohmic contact resistance after treatment may be attributed to both the removal of oxide and C-containing contamination and the improvement of the surface electronic properties

by the KOH-based treatment. The optimization of this treatment is being present. The effect of various parameters of KOH-based treatment, such as treatment time and KOH solution concentration, will be reported.

10:00 AM Break

10:20 AM +
Characterization of Rhenium Schottky Contacts on n-Type AlxGa1-xN at High Temperatures: *L. Zhou*[1]; A. T. Ping[1]; J. Redwing[2]; I. Adesida[1]; [1]University of Illinois, Dept. of Elect. and Comp. Eng., Microelectronics Lab, MC-249, Urbana, IL 61801-2355 USA; [2]ATMI/Epitronics, Phoenix, AZ 85027 USA

The study of Schottky barrier contacts on AlxGa1-xN is of great importance for high power and high temperature heterostructure field effect transistors (HFETs). For the gate contact of such devices, metals are needed which form high barrier heights and are stable at elevated temperatures. Schottky barrier heights of a variety of metals (i.e. Ni, Au) to n-type GaN have already been characterized [1]. However, the majority of these metals are unsuitable for high temperature operations. Tungsten and rhenium have been predicted to form thermodynamically stable contacts on GaN [2]. Rhenium is the more promising of the two because of its higher barrier height to n-GaN and has been demonstrated the capability to withstand annealing temperatures of 700ºC for up to 10 minutes without performance degradation. Thus far, no Schottky characteristics have been reported for Re on AlGaN. This study is important for the fabrication of gate contacts on AlxGa1-xN HFETs. In this paper, we report on the Schottky characteristics of rhenium on AlxGa1-xN (x=0.1, 0.2 and 0.3) at elevated temperatures. The electrical and materials characteristics of Re Schottky contacts on AlxGa1-xN (x=0, 0.1, 0.2 and 0.3) grown by MOCVD on sapphire substrates were investigated. The effective barrier heights were obtained from current-voltage-temperature (IVT) and capacitance-voltage (CV) measurements and were found to increase with higher aluminum concentration. The Re contacts on GaN did not degrade until 800°C while those on AlxGa1-xN degraded after annealing at 600°C for 10 min. Secondary ion mass spectroscopy (SIMS) depth profiles were used to study the Re/AlGaN interfaces following high temperature treatments.

10:40 AM
Improved Surface Morphology and Thermal Stability of Al/Ti/n-GaN: *Joon Seop Kwak*[1]; Suzanne E. Mohney[1]; R. Scott Kern[2]; [1]The Pennsylvania State University, Dept. of Mats. Sci. and Eng., University Park, PA 16802 USA; [2]Hewlett Packard Company, 370 W. Trimble Rd., San Jose, CA 95131-1008 USA

Ti/Al ohmic contacts are widely used on n-type GaN. Rough surface morphologies after the contacts are annealed and degradation upon high temperature aging have been reported. Ti and Al also provide the first layers in some of the more complicated multilayer contacts that are currently in use. Nevertheless, little work has been performed to evaluate the role of the relative amounts of Ti and Al on the contact resistivity, long term thermal stability, and phase formation in Al/Ti/n-GaN contacts. In this study, we find that the overall composition of the contacts greatly influences all three of these characteristics. Ti/Al contacts with Ti layer thicknesses of 15, 35, 55, or 75 nm and Al layer thicknesses of 115 nm were sputtered on lightly doped n-GaN (n=5x10^{16}cm^{-3}) grown by metalorganic chemical vapor deposition. The contacts were annealed in a rapid thermal annealing furnace in Ar. For contacts with thin Ti layers (15 and 35 nm), contact resistivities of 2x10^{-5} W cm^2 were measured after 15 s anneals at 600-750ºC and 600-800ºC, respectively. For contacts with thicker Ti layers (55 and 75 nm), higher contact resistivities near 10^{-4} W cm^2 were obtained upon annealing for 15 s in the same temperature range or for longer times at 600ºC. Upon annealing the contacts with the thicker Ti layers for 15 s at 950ºC (55 nm layer) or 1000ºC (75 nm layer), however, the contact resistivities dropped to 2x10^{-5} W cm^2. These values are comparable to those obtained for contacts with thinner Ti layers annealed at lower temperatures. Although they required higher annealing temperatures to reach comparable contact resistivities, the ohmic contacts with the thicker Ti layers provided several advantages. They presented smooth surface morphologies when viewed in a scanning electron microscope,

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even after they were annealed at temperatures near 1000°C. Contacts with thin Ti layers yielded rough surface morphologies after they were annealed at only 600°C. The contacts with the thicker Ti layers also suffered much less severe degradation during long-term aging in encapsulated quartz tubes at 600°C. The differences between the contacts with the thin and thick Ti layers can be explained when the contact metallurgy is examined. The ohmic contacts with thin Ti layers still contain elemental Al after annealing since the ratio of Al:Ti exceeds that required to form the most Al-rich titanium aluminide on the binary phase diagram. The elemental Al agglomerates when annealed or aged near its melting point of 660°C, resulting in rough surface morphologies upon annealing and an increasing metal sheet resistance upon aging. In contrast, the Al in the contacts with the thicker Ti layers is present only in intermetallic phases with higher melting points, conferring greater thermal stability. Important differences in the phase formation at the interface between the contacts and GaN, which influence the annealing conditions required for achieving ohmic contacts, are also examined.

11:00 AM +

A New Approach to Thermodynamically Stable Contacts for Binary Wide Bandgap Semiconductors: *Ilan Shalish*[1]; Yoram Shapira[1]; Moshe Eizenberg[2]; [1]Tel-Aviv University, Dept. of Phys. Electr., Tel-Aviv 69978 Israel; [2]Thechnion - Israel Institute of Technology, Dept. of Mats. Eng., Haifa 32000 Israel

One of the main bottlenecks in the design of high-temperature electronic devices, based on SiC or GaN, is the thermodynamic stability of the substrates with the contact metallizations. "Silicide-like" contacting technology, as is widely used in silicon devices, would be highly desirable, if feasible. However, for various reasons, such a technology is still lacking for binary semiconductors. In this work, a new approach is suggested, where a bi-metal contact is constructed. In this approach, each metal preferentially reacts with another component of the semiconductor, resulting in a thermodynamically stable sequence of metallic layers and an intimate adherent contact. This approach is studied on several systems: <SiC>\Ti\Co, <SiC>\Ti\Pt, and <GaN>\Ti\Pt, with various thickness ratios of the two metals. For concept demonstration, we show preliminary results obtained at the <SiC>\Ti(30nm)\Pt(30nm) system. Depth profiles and phase identification were made using x-ray photoelectron spectroscopy on as-deposited and annealed samples (500°C to 900°C for 1h durations). Scanning electron microscopy and electron dispersive spectroscopy were used on cross-sections of the same samples. We show that the reaction of the Ti\Pt bi-layer with the SiC results in a thermodynamically stable contact, useful for high-temperature electronics applications, if properly designed thicknesses of Ti and Pt layers are used. The following sequence of processes is anticipated: first, Pt and Ti inter-diffuse, forming a TiPt intermetallic. Next, Pt reacts with the SiC substrate, while the remaining carbon is gettered by either free Ti, or by Ti extracted from the TiPt intermetallic, to form the more stable TiC. As a TiC layer is built up, Pt transport through this formed barrier is reduced and eventually altogether inhibited. The Pt atoms located beyond the barrier react with the substrate, forming a PtSi phase, which is thermodynamically stable with both the substrate and the TiC adjacent layer.

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Metallization Schemes for High Temperature Electrical Contacts to Silicon Carbide: Taehoon Jang[1]; Gerald W. M. Rutsch[2]; Bruce Odekirk[3]; *Lisa M. Porter*[1]; [1]Carnegie Mellon University, Mats. Sci. & Eng., 5000 Forbes Ave., Pittsburgh, PA 15213-3890 USA; [2]University of Pittsburgh, Dept. of Phys., Pittsburgh, PA 15260 USA; [3]3C Semiconductor Corporation, 5429 SW Viewpoint Terr., Portland, OR 97201 USA

A major limitation for the development of high temperature devices based on SiC is the stability of all metal/semiconductor and metal/metal interfaces that are to be incorporated between the substrate level and interconnection/packaging level. For example, most metals react with SiC to form carbides and/or silicides. For many metal/SiC systems the kinetics of the reactions in the 300–500°C range are slow, indicating the possibility for SiC device stability at these temperatures for finite but limited times. At temperatures above 600°C many metals have been reported to react with SiC within minutes. The presence of

an oxidizing atmosphere (i.e., in air) at high temperatures adds an additional complication that can result in the degradation of contacts. In the present study metals and compounds that are thermodynamically stable with SiC were investigated for intimate contacts to SiC; some contacts with reportedly slow reaction kinetics with SiC were also investigated. After annealing at 1000°C for 15 min., TaC contacts were ohmic on n-type (2 x 1019 cm-3) 6H-SiC with specific contact resistivities (SCRs) of 2.1 x 10-5 W cm2 at room-temperature. The calculated specific contact resistivities for these contacts increased slightly with measurement temperature. Osmium contacts annealed at 1020°C for 1 h and 1075 °C for 15 min. displayed ohmic behavior on p-type (1 x 1019 cm-3) 6H-SiC with SCRs of 6.8 x 10-4 W cm2. Current-voltage measurements in air at temperatures to 400°C revealed that overlayers, such as Au or Pt were required to prevent oxidation of both the Os and the TaC contact layers. For example, the addition of Au overlayers on the TaC contacts resulted in a reduction in the SCR by more than an order of magnitude. The average SCRs for these latter contacts ranged from 1.6 x 10-6 to 5.3 x 10-7 W cm2 in the 20–300°C temperature region. The overlayers, while needed for protective layers and/or for lower resistivity layers, form interfaces with the contact layers, which in turn add additional sites for potential reactions to take place. Long term annealing was performed to demonstrate the stability of the interfaces in a controlled ambient. Current-voltage measurements, including SCRs, as a function of temperature will be reported for a number of multilayer contact schemes and compared with those for the single layer contacts. These results will be correlated with chemical and microstructural characterizations of the interfaces. Current-voltage measurements of Ta and TaC Schottky contacts to p-type 6H-SiC showed good reversibility after ten cycles in air between R.T. and 400°C. These results indicate 1) that the interfaces remained unreacted and 2) that O had less effect on these contacts than on the ohmic contacts discussed above. A comparison of the results of ohmic and Schottky contacts will be presented and discussed with regards to thermal stability issues. The authors wish to thank the National Sci. Foundation (Grant No. ECS-9713371) and BMDO (Contract No. DASG60-96-C-0157) for support of this research, Prof. R.F. Davis for providing SiC substrates (through the DARPA under Contract # N00014-95-1080) and Prof. W.J. Choyke for providing facilities and assistance for annealing samples.

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Effect of Si1-xCx Interface Layer on the Properties of Metal Contacts to p-type SiC: *Johnson Olufemi Olowolafe*[1]; Jun Liu[1]; Sarbajit Datta[1]; [1]University of Delaware, Elect. and Comp. Eng., Newark, DE 19716 USA

The role of Si1-xCx alloys on the physical and electrical properties of metal contacts to p-type a-SiC is presented. P-type Si1-xCx alloys were deposited on p-type 4H- or 6H-SiC substrates using either the molecular beam epitaxy deposition technique or by co-sputtering Si and C using a DC/RF magnetron sputtering system. Using Fourier transform infrared spectroscopy the Si1-xCx alloys were found to precipitate into 3C-SiC, after annealing. Various metals including Co and Ti were deposited on Si1-xCx, as-prepared and annealed. The metal/Si1-xCx/SiC structures were annealed to induce intimate contacts at the interfaces. Rutherford backscattering spectrometry (RBS) technique was used to evaluate film thickness and monitor interface reactions. X-ray diffraction technique was used to characterize Si1-xCx microstructure transformation and intermetallic phases. Distribution of materials was investigated, with and without sample annealing, using Auger electron spectroscopy. Current-voltage characterization of patterned metal/p-Si1-xCx /p-SiC showed ohmic behavior with lower values of contact resistance compared to metal/p-SiC structures. The low ohmic contact resistance values were attributed to the ?bandgap Eng.? due to the precipitation of Si1-xCx into the 3C-SiC (Eg = 2.3 eV) on the a-SiC substrates (Eg = 3.0-3.2 eV).

Session BB. Etching and Passivation of Compound Semiconductors

Friday AM   Room: State Street
July 2, 1999   Location: University Center

Session Chairs: Marian Hargis, Purdue University, West Lafayette, IN USA; Carol Ashby, Sandia National Laboratories, Albuquerque, NM USA

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In Situ Etch and Regrowth of a InAs/AlGaSb Heterostructure: *Giovanni Bellomi*[1]; William. J. Mitchell[1]; Eric Hall[1]; Evelyn L. Hu[1]; [1]University of California Santa Barbara, QUEST, Santa Barbara, CA 93106-5050 USA

Structures that use InAs quantum wells (Q.W.) embedded in wider gap, lattice matched AlGaSb barriers facilitate a number of applications such as superconducting weak links, infrared devices, quasi-one-dimensional electron transport structures, and high electron mobility transistor devices. In a majority of these applications, the top AlGaSb layer must be removed (to some extent) to allow direct contact with the InAs Q.W. Standard ex-situ processing methods (e.g., wet etching and/or sputter cleaning and etching) expose the InAs surface to air and result in oxide formation as well as introduce damage within the Q.W. itself during oxide removal and/or etching. In this work, we present a complete in situ technique that is designed to preserve the quality of the exposed InAs surface. The principal components include a selective thermal Cl2 etch of the top barrier layer designed to stop at the InAs Q.W., and an in situ post-etch anneal under As2 flux to clean and reorder the InAs surface. We have used Auger electron spectroscopy, atomic force microscopy, and transmission electron microscopy to monitor the compositional and morphological dependence of the exposed InAs surface on different processing variables such as etching temperature, methods of removing the initial barrier layer oxide (e.g., thermal desorption vs. Ar+ sputtering), and "overetch" time (i.e., the time that the InAs surface is exposed to Cl2). Samples were etched by the thermal chlorine treatment, and an overlying AlGaSb was subsequently regrown by MBE (molecular beam epitaxy). We have made measurements of the electron concentration and mobility of the regrown structures, which provide important insights on the quality of the etch process.

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Inductively Coupled Plasma Selective Reactive Ion Etching of GaAs/InGaP For Device Fabrication: *W. Lanford*[1]; C. Lee[1]; G. Cueva[1]; L. Zhou[1]; I. Adesida[1]; Noren Pan[2]; [1]University of Illinois at Urbana-Champaign, Dept. of Elect. and Comp. Eng., 208 N. Wright St., Urbana, IL 61801-2355; [2]Kopin Corporation, Inc., Taunton, MA 02780

Selective etching of semiconductors is important in the fabrication of devices since it allows accurate control of etch depths. This in turn results in significant process latitude in controlling the electrical characteristics of the devices. An important device that relies critically on selective etching is the high electron mobility transistor (HEMT where the cap-layer has to be removed from the top of the underlying Schottky barrier enhancement layer. Accurate control of the depth is required to achieve uniform threshold voltage across a wafer and from run to run. For the conventional GaAs/AlGaAs/InGaAs pseudomorphic HEMT, both wet and dry etching methods have been extensively investigated for the removal of GaAs on AlGaAs in the gate recessing step. For dry etching, conventional reactive ion etching (RIE) has been the primary method used in these investigations. Although it is usually difficult to achieve the low self-bias plasma voltage that is ideal for the selective etching, work has been done to develop low damage processes for the

gate recess step in the fabrication of these devices. Recent move to GaAs/InGaP/InGaAs pseudomorphic (p-) HEMTs to avoid the effects of defect centers in AlGaAs necessitates the development of selective dry etching for GaAs on InGaP. In this paper, we present our work on the reactive ion etching of GaAs and In0.5Ga0.5P using an inductively-coupled-plasma (ICP) reactor. The investigations were carried out in different gas mixtures namely SiCl4/SiF4 and BCl3/SF6 in order to determine the selectivity of GaAs on InGaP. Also, the investigations examined etch rate variations with gas flow rate, ICP-power, bias voltage and chamber pressure. High selectivity values have been obtained and the results have been used in fabricating GaAs/InGaP/InGaN p-HEMTs. The influence of the plasma parameters on the bare InGaP will be presented in the form of Schottky barrier characteristics. The dc and microwave properties of the HEMT will be presented. Auger electron spectrocopy and x-ray photoelectron spectroscopy of the etched surfaces will be discussed.

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GaAs/AlGaAs Selective Dry Etching by Sawtooth-Wave Modulated Inductively Coupled SiCl4/SF6 Plasma: *Yusuke Matsukura*[1]; Jun Wada[2]; Mizuhisa Nihei[1]; Hitoshi Tanaka[1]; [1]Fujitsu Laboratories Ltd., Compound Semiconductor LSIs Lab., 10-1, Morinosato-Wakamiya, Atsugi, Kanagawa 243-0197 Japan; [2]Fujitsu Quantum Devices Ltd., 1000, Kamisukiahara, Showa-cho, Nakakomagun, Yamanashi 409-3883 Japan

The Inductively Coupled Plasma (ICP) sources are promising for its applicability to the highly-anisotropic etching. However, the selectivity and the anisotropy tend to be incompatible in the GaAs/AlGaAs selective dry etching by the ICP source [1]. We previously reported that the rectangular pulsed-excitation can improve the selectivity of the SiCl4/SF6 ICP selective dry etching [2,3]. However, rectangular pulsed-excitation suffers from the matching problem between the power supply and the plasma. In this report, we applied the sawtooth-wave modulated ICP source to reduce the RF reflection, and showed that the selectivity and the amount of the lateral etching are controlled by the modulation frequency. Our equipment was reported elsewhere [1]. 13.56 MHz excitation power was modulated by the sawtooth-wave signal generated by the function generator. The etching condition was; SiCl4/SF6=20/5 sccm, pressure=0.35 Pa, stage temperature=-5 C, bias power=4 W. The averaged excitation power was set to be 200 W by the conventional power controller. Reflected power was about 40 W, about a half of that in the rectangular pulsed-excitation (about 85 W). This is because of the reduction of the abruptness in the RF power modulation compared to the rectangular pulsed-excitation. Lower RF reflection is much favorable to the practical application. The GaAs etching rate (RGaAs) varied from 830 nm/min at 500 Hz to 610 nm/min at 20 kHz, was almost a monotonous function of the modulation frequency. But at 40 kHz RGaAs was increased up to 720 nm/min in accordance with the bias voltage increase. The AlGaAs etching rate was, on the other hand, rather complicated function of the modulation frequency, and this gives the maximum selectivity of about 150 at 2 kHz and 40 kHz. In all the frequency range we studied (0.5-40 kHz) the selectivity exceeded 100 while that in the CW excitation was below there. We attributed these results to the modulation frequency dependence of the radical density (Nr). The calculation of the temporal response of Nr and its average over the repetition cycle fitted well with the results of RGaAs. The amount of the lateral etching at the 40 kHz was reduced to about 70% of that at the 2 kHz by Nr reduction. This shows the applicability of the sawtooth-wave modulation to the etched feature control. In summary, we investigated the sawtooth-wave modulated SiCl4/SF6 ICP selective dry etching, and found that selectivity and etched feature can be controlled by the sawtooth-wave modulation frequency. [1] Matsukura, Y. et al., Proceedings of the 19th Symposium on Dry Process, 223(1997). [2] Matsukura, Y. et al., Extended Abstracts (The 45th Spring Meeting, 1998); The Japan Society of Applied Physics and Related Societies, 30pQ4(1998). [3] Matsukura, Y. et al., submitted to The Journal of Vacuum Sci. and Technology B

FRIDAY AM

9:20 AM

Air-Stable Surface Passivation of III-V Semiconductors and Application to Devices: *Carol I. H. Ashby*[1]; Kevin R. Zavadil[1]; Albert G. Baca[1]; Ping-Chih Chang[1]; B. E. Hammons[2]; Michael J. Hafich[1]; [1]Sandia National Laboratories, Dept. 1711, MS 0603, P.O. Box 5800, Albuquerque, NM 87185-0603 USA; [2]Emcore West, 10420 Research Rd. SE, Albuquerque, NM 87123 USA

High surface recombination velocities and/or Fermi-level pinning due to a high density of mid-gap surface states ($>10^{12}/cm^2/$) have diminished the performance of heterojunction bipolar transistors (HBTs) and delayed the realization of metal-insulator-semiconductor (MIS) devices in III-V compound semiconductors. Reaction of the GaAs surface with sulfur or its compounds produces a dramatic decrease in the interface states responsible for surface recombination and Fermi-level pinning. However, most sulfur-treated surfaces rapidly reoxidize, returning to their original high density of mid-gap states. We have developed a new method whereby a high-quality semiconductor surface is preserved against air oxidation using photosulfidation followed by reaction with a suitable metal ion in aqueous solution. This process has been applied to prefabricated HBTs to drastically reduce the current gain dependence on surface area. It is also robust against silicon oxynitride encapsulation in a high-density plasma deposition system, making it suitable for fabrication of devices. UV-photosulfidation is employed to deposit a monolayer of sulfide on either n- or p-GaAs. This is followed by reaction with a suitable metal ion to produce a moderately air-stable passivation that is initially a factor of 2 better than previously reported S-only passivations. All metal ions studied to date produced improved photoluminescence (PL) intensity and greater air stability of the improved surface relative to the sulfided surface alone, which returns to the native oxide value within one day. While some metals permit decay of PL intensity to values near the native oxide surface over a period of several days, others produce long-term improvements. Long-term stability correlates with the preferred coordination geometry of the metal ion and the size similarity of the metal ion to Ga. For some metal ions, the initial superior passivation remains stable for tens of days in air and can be retained indefinitely by dielectric encapsulation using a room-temperature high-density-plasma-deposited silicon oxynitride. The mild chemical nature of this process permits passivation of exposed surfaces of prefabricated devices, such as AlGaAs and InGaAs HBTs. Both large- and small-area HBTs show improved current gain following passivation (improvement in collector-base current gain of 7.8% for 100x100 and 78% for 2.5x5 mm² devices). After long-term air exposure (>600 days), the passivation remains equal to that produced by the best S-only processes reported to date. XPS studies of the metal-stabilized surfaces show the presence of additional As-associated surface species that are not observed with S-only passivations. The long-term air stability correlates with these surface species that probably involves interactions with both oxygen and metal ions. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Dept. of Energy under Contract DE-AC04-94AL85000.

9:40 AM

Effects of Chemical Treatments and Sulfide Passivation on Surface Recombination in GaN: *G. L. Martinez*[1]; M. R. Curiel[1]; *B. J. Skromme*[1]; R. J. Molnar[2]; [1]Arizona State University, Dept. of Elect. Eng. and Center for Solid State Electronics Research, P.O. Box 876206, Tempe, AZ 85287-6206 USA; [2]Lincoln Laboratory, Massachusetts Institute of Technology, Rm. E-124D, 244 Wood St., Lexington, MA 02173-9108 USA

Gallium nitride is currently the subject of intense investigation for optoelectronic and high frequency, high power, high temperature electronic applications. However, very little is currently known about the properties of GaN surfaces, the degree of surface recombination that is present on air-exposed surfaces, and the effects of chemical surface treatments or passivation on the surface recombination velocity. In this work, we show that the room-temperature photoluminescence (PL) intensity is significantly reduced by surface recombination, and that surface passivation by inorganic sulfide solutions increases the PL intensity by factors of 5-6 in n-type GaN(0001) layers grown by either hydride VPE or MOCVD. The intensity drops slightly in the first day after treatment, but subsequently remains a factor of 3-4 higher than the untreated surface for at least several months, showing that the passivation effect is stable in room air. A wide variety of sulfidation methods was investigated, including solutions of ammonium sulfide in water, isopropanol, methanol, and butanol; sodium sulfide; and sulfide mixtures. The effects of heating, illuminating, or bubbling oxygen through the solution and adding excess S to the solution were investigated, as well as vacuum evaporation of arsenic sulfide. Photochemical effects are also observed in some cases under ultraviolet laser excitation. A systematic investigation of the effects of other chemicals commonly used in device processing was also performed. Factors of 2-2.5 improvement in PL intensity were observed for treatment in buffered oxide etch or hydrochloric acid, with smaller improvements for sulfuric, nitric, acetic, and phosphoric acids. Treatment with hydrogen peroxide or sodium or potassium hydroxide degrades the intensity by as much as 30%. Bromine-methanol has little effect. The relationship between the surface chemistry and recombination velocity and potential applications of the sulfide passivation treatment will be discussed.

10:00 AM   Break

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Investigation of the Chemisorption and Reaction of Chlorine with the GaN (0001) Surface: *Jingxi Sun*[1]; K. A. Rickert[2]; L. Zhang[1]; A. B. Ellis[2]; F. J. Himpsel[3]; T. F. Kuech[1]; [1]University of Wisconsin-Madison, Chem. Eng. Dept., 1415 Eng. Dr., Madison, WI 53706 USA; [2]University of Wisconsin-Madison, Chem. Dept.; [3]University of Wisconsin-Madison, Phys. Dept.

Surface-adsorbed chlorine is present in several GaN growth and processing techniques. In chloride-based vapor phase epitaxy of GaN, the growth is achieved through the transport of GaCl, its reaction on the surface and the eventual elimination of a chlorine species as a reaction by-product. Chlorine-containing reagents are extensively used in dry etching of GaN-based materials since both Ga and N form volatile chlorides. The specific surface chemistry of chlorine at the GaN surface is therefore a key aspect to developing a mechanistic model of these processes. In this study, we have used synchrotron-based surface analysis techniques to study the chlorine chemisorption and reaction at GaN (0001) surfaces. Synchrotron radiation allows for the tunability of the kinetic energy of the photoemitted electrons, thereby controlling their escape depth from the surface through the choice of the photon energy. A minimum probing depth of a few atomic layers is possible, making this technique ideal for probing surfaces and adsorbates. In the present study, both core-level photoemission and photoabsorption spectroscopy are employed to determine the surface bonding and coverage of the chlorine as well as the change in the GaN surface Fermi level. In particular, photoabsorption spectroscopy provides information about the absolute coverage of specific elements, whereas photoelectron spectroscopy can yield information regarding the chemical state of the element in question. Photoabsorption spectroscopy can be used to quantitatively determine the abundance of specific elements with submonolayer sensitivity. The unintentionally doped n-GaN films used in this study were grown by metalorganic vapor phase epitaxy (MOVPE) on c-plain sapphire substrates. The GaN surface was treated by dipping in HCl solution for ~ 15 minutes. Cl 2p core-level photoabsorption spectroscopy is used to measure Cl surface coverage. The ratio of N to Ga on the surface within a depth of a few monolayers has been determined by comparing the area of the core-level photoemission peaks of Ga 3d and N 1s. Ga 3d, N 1s, Cl 2p core-level photoelectron spectroscopy are used to detect the surface chemical bonding states by monitoring the chemical shift. The chemical bonding at the surface after chlorination will determine the surface electronic properties. The surface electronic property is investigated by monitoring the shift of the surface Fermi level. The progressive desorption of chlorine from the HCl-treated GaN surface was performed by controlled thermal annealing under ultrahigh vacuum environment. The activation of Cl desorption from GaN surface was estimated by studying the desorption rate as a function of temperature. Our results show that chlorine is present on the 'as-received' GaN surface due to contamination from the air. HCl-based treatment can result in the chlorination of GaN surface that has different surface chemical bonding states from the 'as-received' GaN surface for both N and Cl. This is attributed to the removal of the top N-rich surface layer on the 'as-received' GaN surface by the HCl solution, and subsequent reaction of HCl with the resulting fresh GaN sur-

face. HCl-based treatment can improve the surface electronic properties by reducing the surface band bending of ~ 0.7 eV, which is attributed to the reduction of surface state density. Cl forms chemical bonds with both N and Ga on the HCl-treated surface. There are two different GaCl-based chemical bonding states. One of the GaCl based chemical bonding contributes to the reduction of surface band bending, which disappear at ~200 C thermal annealing. The ratio N-to-Ga increases dramatically during thermal annealing under 200°C, which can be attributed to the desorption of GaCl from the HCl-treated GaN surface. The N-Cl related chemical bonds are eliminated at ~ 300°C annealing without a surface Fermi level shift. These results allow for a comprehensive picture of chlorination of the chlorination of GaN surfaces.

10:40 AM

Photoluminescence Measurements of Dry Etch Damage in GaN:

Elaine D. Haberer[1]; Ching-Hui Chen[2]; Monica Hansen[1]; Evelyn L. Hu[2]; [1]University of California, Santa Barbara, Mats. Dept., Santa Barbara, CA 93106 USA; [2]University of California, Santa Barbara, Elect. and Comp. Eng. Dept., Santa Barbara, CA 93106 USA

In recent years, nitrides have gained popularity for use in optoelectronic devices, high-power devices, and high temperature/caustic environment device applications. The remarkable chemical and thermal stability which make the nitrides attractive for these applications also make device processing difficult. The nitrides are resistant to most wet etching techniques, therefore dry etching is generally used. Ion damage created by dry etching can be deleterious to the electrical and optical properties of semiconductor materials. In smaller bandgap materials systems, such as GaAs, the range of damage for 300 eV ions is greater than 1000 A. It is generally believed that nitride materials are relatively impervious to ion damage, however the range of the ion damage has not been measured. In this study, a quantum well (QW) probe is used to evaluate ion damage. The structure consists of five 30 A GaN/InGaN nominally identical quantum wells capped with a thin layer of low temperature GaN (70 A) and a thick layer of GaN (1000 A). Some of the QW samples were etched for varying times with chemically assisted ion beam etching (CAIBE) using a 5/5 sccm Cl_2/Ar^+ gas flow rate, beam energy of 500 eV, and beam current density of 0.4 mA/cm^2. The GaN etch rate with these parameters is approximately 500 A/min. To single out the effect of ion bombardment, some of the samples were bombarded for varying times with Ar^+ ions using the same ion beam parameters as the samples etched with CAIBE. Room-temperature photoluminescence (PL) measurements were taken before and after ion bombardment. A comparison of the PL spectra shows decreased intensity following ion bombardment. Samples etched with CAIBE experienced less PL intensity loss than those only bombarded with Ar^+ ions, showing that CAIBE produces less damage in the material. These findings suggest that even in GaN, low energy ion damage can extend greater than 1000 A causing optical loss. Furthermore, the range of ion damage observed in GaN is comparable to or greater than that observed for GaAs under similar bombardment conditions. Finally, chemical enhancement of the etch process reduces damage introduced to the material. The PL intensity of the QWs provides a sensitive assessment of etch-induced damage. The ability to separately control the ion-assisted component and the chemical etch component in these studies should allow us to better understand the mechanisms and propagation of etch damage in the nitride materials, the Ar^+ ions, showing that CAIBE produces less damage in the material. These findings suggest that even in GaN, low energy ion damage can extend greater than 1000 A causing optical loss. Furthermore, the range of ion damage observed in GaN is comparable to or greater than that observed for GaAs under similar bombardment conditions. Finally, chemical enhancement of the etch process reduces damage introduced to the material. The PL intensity of the QWs provides a sensitive assessment of etch-induced damage. The ability to separately control the ion-assisted component and the chemical etch component in these studies should allow us to better understand the mechanisms and propagation of etch damage in the nitride materials.

11:00 AM

A Simple Wet Etch for GaN:

Jennifer A. Bardwell[1]; Ian G. Foulds[1]; James B. Webb[1]; Haipeng Tang[1]; [1]National Research Council of Canada, IMS, Bldg. M-50, Ottawa, ON K1A 0R6 Canada

Compared to other III-V semiconductors, GaN is a chemically inert material, which has thus far proved resistant to room-temperature chemical etching. However, the development of low damage etching techniques is still the subject of intense research. A photoelectrochemical technique has previously been developed, which can produce anisotropic (1), dopant selective (2) and smooth (3) etching. Moreover, mesas and pillars can be produced. Unfortunately, this technique can only be used for GaN deposited on a conducting substrate (6H SiC), as the technique requires an electrical contact to be made to the sample. In the present work, a simple, wet etching technique has been developed for GaN. High quality molecular beam epitaxially (MBE) grown GaN can be etched using an SiO_2 mask. The etching is UV assisted, but, unlike previous work, no external metal contact to the GaN is necessary. Etching can be performed on resistive substrates, such as sapphire. The method relies on adding appropriate oxidizing agents to the solution to accept the electrons, which are photoexcited by UV illumination. The holes go towards oxidizing the GaN, eventually resulting in its dissolution. Oxidizing agents such as orthovanadate, iodide, iodate, peroxydisulfate, and hydrogen peroxide have been investigated. The pH of the solution can be varied to optimize the etch rate. Under appropriate conditions, the microscopic anodes and cathodes have been observed using scanning electron microscopy, confirming the electrochemical nature of the etching. For relatively weak light intensities of 1.4 mW/cm^2 at 365 nm, etch rates of up to 1.5 nm per minute have been obtained under non-optimized conditions. Optimized etch rates are expected to be significantly larger, and will be reported when the paper is presented. 1. C. Youtsey, I. Asesida, and G. Bulman, Appl. Phys. Lett., 71(15), 2151 (1997). 2. C. Youtsey, G. Bulman, and I. Adesida, J. Electron. Matls., 27(4), 282 (1998). 3. C. Youtsey, I. Adesida, L. T. Romano, and G. Bulman, Appl. Phys. Lett., 72(5), 560 (1998)

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Photoelectrochemical Etching of GaN for Materials Characterization and Device Fabrication:

I. Adesida[1]; C. Youtsey[1]; D. Selvanathan[1]; T. Pierson[1]; A. Daga[1]; M. Hossain[1]; L. Romano[2]; [1]University of Illinois at Urbana-Champaign, Dept. of Elect. and Comp. Eng. and Microelec. Laboratory, 208 N. Wright St., Urbana, IL 61801-2355; [2]Xerox PARC, Palo Alto, CA 94304

GaN is a wide bandgap material that is chemically stable and unreactive with common mineral acids and bases. An important condition that is common to the techniques developed to date for the etching of GaN is that an external energy is required to initiate and maintain etching. To this end, external energy from ions are utilized in chemically assisted ion beam etching (CAIBE) and reactive ion etching (RIE) while energy from photons in the ultra-violet wavelength is utilized in photoelectrochemical (PEC) etching. Although, there is still work to be done, dry etching, especially RIE, has emerged as the primary technique for fabricating various devices such as lasers, light emitting diodes, and photodetectors in GaN and related materials. A disadvantage of dry etching is the damage that it can create due to ion bombardment. This has been the driving force for the development of low-damage etching processes. The PEC technique is a wet chemical etching method in which the sample forms part of an electrochemical cell on which UV radiation impinges. Preliminary experiments indicate that PEC etching of n-type GaN can result in either smooth or rough etched surfaces [1-3]. Further, it has been demonstrated that whiskers observed for the rough surfaces are due to edge dislocations [3]. In this paper, we will present our results on further investigations on PEC etching of n-GaN and its application to the fabrication of heterostructure AlGaN/GaN devices. Investigations on PEC etching of n-GaN as functions of KOH concentration and UV light intensity have been conducted. The extensive range of surface morphologies obtained will be discussed. Influences of dislocations and crystallography on the surface morphologies will be presented. Applications of PEC etching to gate recessing in the fabrication of heterostructure field effect transistors, and to selective etching in the fabrication of heterojunction bipolar transistors will be discussed. [1] M. Minsky et al., Appl. Phys. Lett. 68, 1531 (1996). [2] C. Youtsey et al., Appl. Phys. Lett., 72, 560 (1998). [3] C. Youtsey et al., Appl.Phys. Lett., 73, 797(1998).

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Development of Photoelectrochemical Etching for Gallium Nitride Device Fabrication: *A. R. Stonas*[1]; P. Kozodoy[1]; C. Chen[1]; H. Marchand[1]; E. L. Hu[1]; [1]University of California at Santa Barbara, QUEST / Elect. and Comp. Eng., University of California, ECE Dept. Box 14, Santa Barbara, CA 93106 USA

Photoelectrochemical (PEC) wet etching has recently demonstrated great promise for device fabrication in the group III nitrides. In particular, the photo-controlled nature of the etch process offers the possibility of extremely high etch selectivity according to the doping and the bandgap of the materials being etched. Youtsey et al.[1] have demonstrated selective undercutting of a buried n-GaN layer within a p-n GaN homostructure. However, the use of thin etch stops is still difficult. Short-range non-uniformities in electrochemical potential produces a wide range of etch rates even within a single layer of GaN. This places particularly stringent requirements on the etch selectivity at the stopping layer. This work examines the optimization of PEC etch selectivity as a method of stopping on thin buried etch-stop layers. We have successfully used both dopant- and bandgap- selective etches, stopping on layers of p-GaN (2000Å) and AlGaN (500Å). These reflect actual device structures (HBTs and FETs) that would benefit from the availability of highly selective low damage etch processes. Further studies will more fully characterize the degree of selectivity obtainable: we will explore the effect of bias, electrolyte composition and concentration, GaN dislocation density, and illumination intensity on selectivity. Optimized PEC etching processes will be applied to a variety of AlGaN/GaN structures. [1]C. Youtsey, G. Bulman, I. AdesidaJournal of Electr. Materials, April 1998, vol.27, (no.4):282-7.

Session CC. Defects and Defect Engineering for Devices

Friday AM   Room: Santa Barbara Harbor
July 2, 1999   Location: University Center

Session Chairs: Steven A. Ringel, The Ohio State University, Dept. of Elect. Eng., Columbus, OH USA; Steve Stockman, Hewlett-Packard Optoelectronics Divison, San Jose, CA USA

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Wafer Edge Misfit Dislocation Nucleation in p/p+ Vapor Phase Silicon: *Petra Feichtinger*[1]; Hiroaki Fukuto[1]; Mark S. Goorsky[1]; Dwain Oster[2]; Jim Moreland[2]; Mohan Rao[2]; [1]University of California, Los Angeles, Dept of Mats. Sci. and Eng., School of Eng. and Applied Sci., 2521 Boelter Hall, Los Angeles, CA 90095-1595 USA; [2]Wacker Siltronic Corporation, 7200 NW Front Ave., Portland, OR 97283

Determining the hierarchy of initial nucleation sources for misfit dislocations is important for both pseudomorphic epitaxial structures and for intentionally relaxed structures. In particular, the role of damage at the wafer periphery has been indicated as a contributor to misfit nucleation, but this factor has not been addressed in depth. We studied the role of edge damage on misfit dislocation formation in p/p+ silicon wafers to determine i) if careful control of the edge treatment could reduce the density of misfit segments and ii) whether other dislocation sources dominated the kinetics of the process. The samples were 150 mm Czochralski grown highly boron doped wafers (2.6×10^{19} cm^{-3}). Different combinations of edge treatments were used during the processing of the wafers to create differences in both the edge shape and roughness. 2-12 mm thick lightly boron doped epitaxial layers (10^{15} cm^{-3}; resulting strain about 10^{-4}) were deposited by vapor phase epitaxy at 1080-1150°C in a single wafer reactor using trichlorosilane as a precursor. Double crystal x-ray topography was used to measure the 60° misfit dislocation segments around the wafer periphery. Misfit dislocations

were not observed to nucleate at any other locations on the wafer surface, indicating that particulates or defects in the substrate did not play an observable role in the formation of misfit segments. A variation of misfit segment lengths was observed. On a local scale, the differences in lengths are attributed to the stochastic nature of t he nucleation process, and longer scale variations stem from the effects of crystallography and of blocking by orthogonal dislocations. Edge treatments which involved polishing steps exhibited great reductions or even the absence of misfit dislocations (<10 cm^{-1}) compared to unpolished edge treatments (~1000 cm^{-1}). In regions where the misfit dislocations were observed, triple axis x-ray diffraction determined that the amount of layer relaxation was consistent with the dislocation density. High temperature (800-1000°C) post growth annealing was studied to determine the stability of the layers against subsequent high temperature device processing.

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Reduction of Defect Induced Leakage Currents by the Use of Nitrided Field Oxides in Selective Epitaxial Growth (SEG) Isolation for Silicon ULSI: *Rashid Bashir*[1]; Tai-chi Su[1]; Gerold W. Neudeck[1]; John P. Denton[1]; [1]Purdue University, Elect. and Comp. Eng., 1285 EE Bldg., W. Lafayette, IN 47906 USA

Background: As silicon devices are scaled down to the deep submicron regime, the cost of device processing is increasing very rapidly. As compared to conventional recessed LOCOS (Local Oxidation of Silicon) or STI (Shallow Trench Isolation), selective epitaxial growth (SEG) of silicon provides a simple and cost effective process for formation of isolated device islands. The key limitation to SEG for device isolation, however, is the presence of defects near the SiO2-Silicon sidewall interface. These defects are caused by the thermal stresses induced at the interface during the cool-down ramp after the SEG growth. Introducing nitrogen into the field oxide to change its thermal expansion coefficient (aT) has been proposed as a means to reduce the sidewall defects. It is known that aT (SiO2) < aT (Si) < aT (Si3O4), and hence nitridation of the field oxide should bring the thermal expansion coefficient of oxide closer to that of silicon. The purpose of this paper is to experimentally demonstrate the reduction of the defect induced leakage currents in SEG silicon grown in nitrided field oxides. Experiments & Results: A 9000Å field oxide was grown and then nitrided in pure NH3 at 1100°C for 60 minutes to result in 14% atomic nitrogen in the film. SEG Silicon was grown at 970°C, 40T using DCS and HCl in a pancake type reactor. P+/N diodes were fabricated with junctions intersecting the sidewall with thermal field oxide (OX diodes) and with nitrided field thermal oxide (NOX diodes). Control diodes were also fabricated with junctions 5μm away from the sidewall interface (OX-5 and NOX-5) to test the intrinsic material quality. The diodes used had perimeter to area ratios ranging from 0.048 to 0.11. The reverse and forward currents of these diodes were measured to study the material and sidewall quality. The reverse leakage current density, JR (A/cm2), was measured at 0.2V and 1V. The perimeter reverse saturation current density JRP(A/cm), was extracted from the slope of JR vs P/A. The values of JRP(A/cm) at 0.2V were 2.59x10-10 A/cm for the OX diodes and 0.63x10-10 A/cm for the NOX diodes. Thus the values for NOX diodes were about 5X lower than the OX diodes. The perimeter reverse saturation current density JRP(A/cm) for the OX-5 diodes at 1V reverse bias was extracted to be 0.55x10-10 A/cm and hence is close to the NOX diodes. In the forward regimes, the ideality factor of the diodes is a good indicator of the material quality. The forward characteristics of the diodes were also measured to extract the perimeter saturation current densities. The results again showed a similar trend, i.e., the NOX devices were significantly improved when compared to the OX devices. These reverse and forward measurements clearly show the improvement and reduction in the sidewall leakage currents due to the presence of the nitrided field oxide, thus proving the fact that the presence of the nitrided field oxide does reduce the thermal induced defects and hence the leakage currents. Further process details and experimental results will be presented in this paper.

Selective SiGe Nanostructures Grown by UHVCVD: *Thomas Andrew Langdo*[1]; Matthew T. Currie[1]; Gianni Taraschi[1]; Eugene A. Fitzgerald[1]; [1]Massachusetts Institute of Technology, Dept. of Mats. Sci. and Eng., 77 Massachusetts Ave., Cambridge, MA 02139 USA

Selective epitaxial growth (SEG) of SiGe on patterned SiO_2/Si substrates by ultra-high vacuum chemical vapor deposition (UHVCVD) shows promise for the fabrication of novel Si microelectronic structures such as self-aligned bases in BJTs, raised Si CMOS contacts, 3-D Si CMOS devices, and defect engineered Ge structures on Si. This work explores the limiting conditions of selective growth with SiH_2Cl_2/H_2 and $SiH_4/GeH_4/H_2$ between 550-750ºC, without the addition of Cl_2 or HCl, to fabricate Si-based nanostructures on Si/SiO_2 wafers patterned by interferometric lithography. In addition, we show that pure Ge grown selectively on Si in such nanoholes can be highly perfect at the top surface compared to conventional highly lattice-mismatched growth on planar substrates. To develop a selective growth process at low temperature (650ºC) the role of SiH_4 and H_2 pressure on selectivity was investigated on Si/SiO_2 substrates patterned by conventional optical lithography. Decreases in SiH_4 pressure dramatically increased the incubation time and maximum selective thickness to 1000 sec and 75 nm while further optimizing the H_2 pressure results in incubation times as long as 1400 seconds and selective Si thicknesses of 100 nm. At 750ºC SiH_2Cl_2 exhibits much higher selectivity than SiH_4. Using SiH_2Cl_2/H_2 selective growth we have demonstrated perfect filling of 50-100 nm diameter holes formed by interferometric lithography in 120 nm thick thermal SiO_2. No defects were visible at the growth interface or along the oxide sidewall by high resolution transmission electron microscopy (HRTEM). However, twins and stacking faults were observed at the merging of ELO (epitaxial lateral overgrowth) growth fronts from adjacent holes. For growth in 50-100 nm holes facets evolve from slow-growing (311) facets in the hole to (111) outside the hole, resulting in a 50% growth rate reduction compared to (100) Si. P-type doping with B_2H_6 as high as $5x10^{19}/cm^3$ and n-type doping with PH_3 as high as $3x10^{19}/cm^3$, confirmed by spreading resistance profiles (SRP), have been achieved under selective growth conditions. Current -voltage characteristics of diodes grown in 100 nm structures will be presented. It is well known that due to the 4% lattice mismatch, direct growth of Ge on Si results in an extremely high density of threading dislocations which degrade device performance. By a combination of interferometric lithography Si/SiO_2 substrate patterning and Ge selective epitaxial growth we have demonstrated threading dislocation blocking at the oxide sidewall which shows promise for dislocation filtering and the fabrication of low defect density Ge on Si for III-V device integration. These results confirm that "epitaxial necking" can be used to reduce threading dislocation density in any lattice-mismatched system. Results on Ge epitaxial lateral overgrowth (ELO) on interferometric lithography patterned Si/SiO_2 substrates will be presented.

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Minority Carrier Properties and Defects in MBE-Grown AlGaAs/GaAs Heterostructures on Ge: *John A. Carlin*[1]; John J. Boeckl[1]; Steven A. Ringel[1]; Brian M. Keyes[2]; [1]The Ohio State University, Elect. Eng., 2015 Neil Ave., Columbus, OH 43210 USA; [2]National Renewable Energy Laboratory, Golden, CO 80401 USA

Epitaxy of III-V compounds in general, and GaAs in particular onto group IV substrates is receiving significant attention across a wide range of device technologies, from the development of optoelectronic integration with Si VLSI using graded GeSi buffers to III-V space solar cells grown on Ge substrates. For such applications, issues that affect minority carrier properties are among the most important for achieving optimum optoelectronic device performance. In particular, minority carrier recombination rates are extremely sensitive to the presence of defects, which are inherent in such heterovalent and heteroepitaxial structures. Hence it is important to understand how specific defects associated with these structures affect minority carrier properties, since in addition to the general, fundamental interest of correlating electronic and structural properties, this impacts optimum design of III-V devices integrated onto group IV substrates. In this paper, we investigate the dependence of minority carrier lifetime and interface recombination velocity on the range of structural defects that can be associated with slightly mismatched, polar/nonpolar GaAs/Ge interfaces formed

by molecular beam epitaxy (MBE). N-type ($2x10^{17}$ cm^{-3}) AlGaAs/GaAs/AlGaAs double heterostructures (DH's) were grown on offcut (001) Ge using a range of nucleation and surface preparation conditions to intentionally incorporate specific structural defects within the DH structure - antiphase domains (APD's), dislocations and stacking faults. Plan-view and cross section TEM and optical microscopy confirmed that the range of nucleation conditions provided sets of samples containing (i) no major structural defects, (ii) APD's alone, and (iii) APD's, dislocations and stacking faults. Time-resolved photoluminescence measurements at 300K were used to determine the bulk minority carrier lifetime and AlGaAs/GaAs interface recombination in these structures for direct correlation with the defects present within each set of samples. For optimally grown DH structures with no APD's and undetectable threading dislocation density, a bulk minority carrier lifetime of 20 nsec with an AlGaAs/GaAs interface recombination velocity of 8000 cm/s were measured, comparable to homoepitaxial growth on GaAs and indicative of the high electronic quality that can be achieved under proper conditions. For samples grown under conditions leading to APD's, stacking faults and threading dislocations together, these values were substantially degraded to 0.5 ns and $1.5x10^5$ cm/s, respectively, indicating the strong impact that only minor changes in growth nucleation have on electronic properties of the III-V overlayers. This highlights the great sensitivity of minority carrier properties on the formation of the heterovalent GaAs/Ge interface. We are currently investigating the minority carrier properties for structures containing APD's alone from which we expect to separate the roles of APD's from dislocations and perhaps stacking faults with regard to minority carrier recombination. A complete correlation along with the specific growth nucleation variables considered in this study (Ge cleaning, annealing, GaAs nucleation, etc.) will be presented.

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Performance and Microstructure of Visible Light-Emitting Diodes Grown on High-Quality InGaP/GaP Epitaxial Transparent Substrates by MOVPE: *Andrew Y. Kim*[1]; [1]MIT, Dept. of Mats. Sci. and Eng., MIT 13-4025, 77 Massachusetts Ave., Cambridge, Massachusetts 02139 USA

InxGa1-xP graded buffers grown on GaP (InxGa1-xP/GaP) are attractive materials for light-emitting diodes (LEDs) because they provide an epitaxial transparent substrate technology versus the etch and wafer-bond processing necessary in the current transparent substrate technology. Earlier work with InxGa1-xP/GaP LEDs showed dropping external quantum efficiency beyond operating wavelengths of 600 nm, which later materials characterization work showed was due to dramatically escalating dislocation density with continued grading beyond xIn ~ 0.3. This is surprising, since extensive experimental and theoretical work has shown that strain relaxation in graded buffers is a steady-state process that should feature a nearly steady-state dislocation density. Recent work with GexSi1-x/Si identified the formation of dislocation pileups as the primary cause of escalating dislocation density. With this new insight into dislocation dynamics in graded buffers, we have revisited the problem of producing high-quality InxGa1 -xP/GaP LEDs. To engineer high-quality transparent substrate materials, we have explored the evolution of microstructure and dislocation dynamics in InxGa1-xP/GaP grown by metal-organic vapor phase epitaxy. We found that, initially, dislocation glide kinetics limit relaxation and dislocation density decays exponentially with growth temperature. With continued grading, {110} planar defects orthogonal to the (001) growth surface evolve, which we call branch defects due to their appearance in plan-view. Branch defects feature strong local strain fields that pin dislocations and cause dislocation pileups, leading to escalating dislocation density. The evolution and morphology of branch defects are controlled by growth conditions. While graded buffers are typically grown under constant conditions, we found that varying growth conditions were necessary to both maximize dislocation glide kinetics and control branch defects. Through a two-step process optimization strategy, we recovered a nearly steady-state dislocation density of < 5´106 cm-2 out to xIn ~ 0.45, the lowest dislocation densities ever reported at such high indium compositions. Using these new high-quality substrate materials, we grew a series of InxGa1-xP/GaP transparent substrate LEDs. These LEDs show a turn-on voltage of approximately 1.5 V and reach 35 A/cm2 by 2.0 V. Initial results show increasing brightness from 590

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nm to 650 nm, in contrast to the severe degradation seen beyond 600 nm in earlier work. The promising results suggest that a full range of efficient green to red LEDs should be possible on epitaxial transparent substrates of InxGa1-xP/GaP. If a steady-state dislocation density can be maintained to even higher indium compositions, LEDs with operating wavelengths ranging into the infrared could also be produced, which would surpass the capabilities of the current In0.5(AlyGa1-y)0.5P/GaAs LED technology. We will present an analysis of LED performance versus dislocation density and microstructure and compare these results with earlier InxGa1-xP/GaP LED work and current LED technologies.

10:00 AM Break

10:20 AM
Photoreflectance Study of Phosphorus Passivation of GaAs: *Richard Beaudry*[1]; Xiangang Xu[1]; Jinsheng Hu[1]; Simon P. Watkins[1]; [1]Simon Fraser University, Dept. of Phys., 8888 University Dr., Burnaby, BC V5A 1S6 Canada

Phosphorus passivation has recently received significant interest as a technique for reducing the density of surface traps in GaAs. The effect of phosphorus exposure on room-temperature photoluminescence (PL) intensity was recently studied using X-ray diffraction to determine the surface phosphorus coverage. In that work we showed that a coverage of roughly 2 monolayers was necessary to produce the maximum observed 300-fold PL enhancement. In this work we have observed Franz-Keldysh oscillations in the photoreflectance spectra of (001) undoped-N+ structures with and without phosphorus passivation. Using this technique we observed a significant reduction in the surface electric field for phosphorus passivated GaAs compared with untreated, air-exposed GaAs. We discuss the effect of phosphorus coverage on surface Fermi level position and also the results of extended air exposure on the stability of the passivation effect. Passivation was carried out using exposure to tertiarybutylphosphine vapour in an MOVPE reactor at 500-600°C.

10:40 AM
Reversal of Electrical Stress Degradation in Fully Self-Aligned InP/GaAsSb/InP DHBTs by a Surface Treatment in Ozone: *Colombo R. Bolognesi*[1]; *Noureddine Matine*[1]; Georg Soerensen[1]; Xangang Xu[2]; Simon P. Watkins[2]; [1]Simon Fraser University, School of Eng. Sci., Compound Semiconductor Device Laboratory, 8888 University Dr., Burnaby, BC V5A 1S6 Canada; [2]Simon Fraser University, Dept. of Phys., 8888 University Dr., Burnaby, BC V5A 1S6 Canada

Electrical bias stressing of heterojunction bipolar transistors (HBTs) can result is a degradation of the common emitter current gain b due to an increase in both the base current and its ideality factor n_B. It is widely believed that such bias stress tests induce the formation of defects which act as GR centers at either at the emitter/base junction or in its vicinity at the emitter mesa. Self-aligned devices are particularly sensitive to this type of degradation. In the present work we demonstrate that the transistor degradation in InP-based HBTs can be reversed by an ozone treatment, and identify the physical location of the generated defects. MOCVD-grown fully self-aligned InP/GaAsSb/InP DHBTs with a C-doped GaAs$_{0.51}$Sb$_{0.49}$ base were electrically degraded by bias stressing under various biases and displayed a significant increase in the base current ideality factor from a pre-stress value of n_B=1.15 to n_B=1.6. As expected for a C-doped base, the collector current characteristic remained unaffected by the bias stress test with n_C=1.05. We have discovered that a UV-ozone plasma treatment almost completely reverses the electrical damage and returns the transistor characteristics to their pre-stress state with n_B=1.15-1.20. It is believed that the UV-ozone treatment produces an oxide film which restores the stoichiometry of the oxide/semiconductor interface and removes damage at the semiconductor surface [see Driad et al., IPRM98 Proc., pp. 459-462]. Because the intrinsic E/B junction is shielded from the ozone treatment, our results indicate that the degradation in bias stress test arises mainly due to defect generation at the emitter periphery in HBTs. We also found that the same UV-ozone treatment could restore a gain of >10 in a small area in MBE-grown InP/GaInAs HBT operated at a collector current density J_C=0.008 A/cm^2. The potential of UV-ozone treat-

ments for HBT reliability improvement will be discussed in the presentation.

11:00 AM +
Traps in Pseudomorphic InGaAs/AlGaAs/GaAs HEMTs Measured by Deep Level Capacitance and Current Transient Spectroscopy: *Evelyn N. Wang*[1]; Mike Wojtowicz[1]; Dwight C. Streit[1]; [1]TRW, Inc., Electr. & Tech. Div., 1 Space Park, R6/2573, Redondo Beach, CA 90278 USA

We have investigated the trap characteristics of single and double heterostructure pseudomorphic InGaAs/AlGaAs/GaAs HEMTs using Fourier transform deep level transient spectroscopy (DLTS) [1]. Both current and photo-induced capacitance transient measurements were used. The single heterostructure HEMT has an InGaAs channel bounded by an AlGaAs donor layer and a GaAs buffer layer. The double heterostructure HEMT has an InGaAs channel bounded by an AlGaAs donor and buffer layer. These device profiles are used for low and high power applications at frequencies from 2 to 100 GHz. Characterization of the traps present in these HEMTs is critical due to their negative impact on device noise, process reproducibility, and circuit performance. We will discuss the trap types and concentrations present in these profiles and the affect of the AlGaAs buffer layer on the trap characteristics. In addition, the affect of the traps on the measured photoluminescence spectra will be presented. The material profiles were verified using photoreflectance and xray rocking curves. In the single heterostructure profile signals related to the AlGaAs ME1 and ME5 traps are observed in the DLTS spectra [2]. In addition, signals observed both in the capacitance and current measurements indicate the presence of interface traps spanning an energy range of 0.1 eV. All of the signals are present at gate biases from 0.4 to ?1.0 V. At ?2.0 V gate bias the signals disappear, indicating they originate from the channel. In the double heterostructure HEMT only the ME1-ME5 signals are observed. These signals also disappear at a ?2.0 V gate bias indicating they originate from the channel. Interface traps are not observed for the double heterostructure profile. This is probably due to the high ME trap concentrations. The higher concentration of ME traps also correlates with a reduction in the channel 4.2K photoluminescence intensity of the double heterostructure profile. [1] S. Weiss, et al. Solid-State Elec., Vol. 31, No. 12, 1988, p. 1733. [2] K. Yamanaka, et al., J. Appl. Phys, Vol. 61, no. 11, 1997, p. 5062.

11:20 AM +
Physical Evidence of Hydrogen Degradation of InP HEMTs: *Roxann R. Blanchard*[1]; Jesus A. del Alamo[1]; Albert Cornet[2]; [1]Massachusetts Institute of Technology, 60 Vassar St., Rm. 39-313, Cambridge, MA 02139 USA; [2]Universitat de Barcelona, Facultat de Fisica, Av. Diagonal, 645-647, Barcelona E-08028 Spain

Hydrogen sensitivity of III-V FETs is a serious and well documented reliability concern. A systematic set of electrical experiments on InAlAs/InGaAs HEMTs on InP has recently revealed that hydrogen affects differently the intrinsic region directly under the gate and the extrinsic regions outside the gate [1]. In the intrinsic region, evidence that hydrogen-induced threshold voltage shifts are due to the piezoelectric effect has prompted the hypothesis that hydrogen reacts with titanium in the gate to form titanium hydride, leading to compressive stress in the gate. In the extrinsic regions, changes in the surface potential of the exposed InAlAs have been proposed to explain a reduction in the channel carrier concentration underneath. In this work, material characterization techniques have been used to independently confirm for the first time that hydrogen exposure leads to the formation of TiH$_x$ and compressive stress in Ti/Pt layers. We have also confirmed changes in the surface of InAlAs after exposure to hydrogen. Titanium hydride formation has been confirmed through Auger Electron Spectroscopy on Ti/Pt test films deposited on 4" Si$_3$N$_4$ covered Si substrates. Compared to control samples annealed in pure N$_2$, samples annealed in forming-gas (5% H$_2$ in N$_2$) at 200°C showed a 1 eV shift in the low-energy Ti peak, and the emergence of a second peak at 5 eV below the main Ti peak. These changes are the characteristic signature of titanium hydride. Subsequent recovery anneals of hydrogenated films performed in N$_2$ at 200°C showed a decrease of the TiH$_x$ peak, and recovery of the Ti peak shift. This shows that the formation of TiH$_x$ is a recoverable process, consistent with device electrical results [1]. Com-

pressive stress after H_2 exposure has been confirmed through in situ radius-of-curvature measurements performed on these same Ti/Pt films annealed at 200°C. The forming-gas annealed sample exhibited an increase in wafer bow >10 mm after only a few seconds of exposure, verifying that the film expands. This volume expansion causes compressive stress in the film. In comparison, wafers annealed in N_2 exhibited no change in wafer bow. Recovery anneals of hydrogenated samples in N_2 show that the film stress is also recoverable. Finally, changes in the native oxide of InAlAs have been confirmed through XPS. In this experiment, HEMT samples with exposed InAlAs were annealed in either N_2 or forming-gas at 200°C. The sample annealed in forming-gas showed an increase of the Al_2O_3/AlAs and In_2O_3/InAs peak ratios, and a reduction of the As_2O_3/(Al,In)As peak ratio. These results indicate that hydrogen decomposes As_2O_3, promotes the formation of Al_2O_3 and In_2O_3, with accompanied H_3As desorption. The independent confirmation of the effects of hydrogen on InP HEMTs presented in this work should be instrumental in identifying a permanent solution to this problem. [1] R. Blanchard et al., Proc. of the IEDM, p. 231, 1998

11:40 AM Late News

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

Friday PM   Room: Corwin East
July 2, 1999   Location: University Center

Session Chairs: Kurt G. Eyink, Wright Patterson AFB, OH USA; John A. Roth, HRL Labs, Malibu, CA USA

1:30 PM

Characterization of p-Dopant Interdiffusion in 1.3 μm InGaAsP/ InP Laser Structures Using Modulation Spectroscopy: *A. Jeager*[1]; Fred H. Pollak[1]; C. L. Reynolds[3]; M. Geva[3]; [1]Brooklyn College of CUNY, Phys. Dept., 3438N, 2900 Bedford Ave., Brooklyn, NY 11210 USA; [3]Lucent Technologies, Bell Laboratories, Breinigsville, PA 18031 USA

Optimization of the p-doping profile of 1.3 ÿm InGaAsP/InP multiple quantum well (MQW) laser structures is an important problem in the design and manufacture of low-cost transmitters for different telecommunication applications. Experimental and modeling results obtained by different groups show that changes of acceptor concentration within different regions of the laser structure significantly affect device characteristics. It was shown theoretically and experimentally that p-doping of the active region in strained MQW InGaAsP/InP lasers can lead to a substantial increase in the differential gain leading to greater maximum modulation frequency. It was also predicted theoretically and shown experimentally that an increase of acceptor concentration in the p-cladding layer adjacent to the active region in 1.3 ÿm bulk active InGaAsP lasers makes it possible to minimize the voltage drop at the p-cladding/separate confinement heterostructure (SCH) interface and to avoid a substantial reduction of the barrier for thermionic emission of electrons from the active region. Therefore, the room-temperature, nondestructive evaluation of the p-dopant profile is of considerable importance for production-line characterization of these devices. Using contactless electroreflectance (CER) and piezoreflectance (PZR) we have investigated three InGaAsP/InP p-i-n MQW laser structures with different p-doping profiles. From the Franz-Keldysh oscillations (FKOs) originating in the total insulating region [i-InGaAsP SCH plus MQWs] we have determined the built-in electric field in this region of the samples. There is a systematic increase in the measured electric field with interdiffusion of the p-dopant due to the reduction of the effective dimension of the i-region. These results are in good agreement with secondary ion mass spectrometry (SIMS) measurements on these samples. In addition the CER/PZR spectra from the MQW region

also exhibits the effect of the interdiffusion. From a comparison of the intersubband transitions in the CER/PZR spectra with an envelope function calculation, including the effects of strain and electric field, we can gain information about parameters such as the well width and in-plane strain of the MQW regions. The values of thse quantities are in good agreement with high resolution X-ray diffraction (HRXRD) measurements.

1:50 PM

Room Temperature Polarized Photoreflectance Hotoreflectance Characterization of GaAlAs/InGaAs High Electron Mobility Transistor Structures Including the Influence of Strain Relaxation: *Ying-sheng Huang*[1]; T. H. Chen[1]; W. D. Sun[2]; Fred H. Pollak[2]; Mark Goorsky[3]; D. Streit[4]; M. Wojtowicz[4]; [1]National Taiwan University of Science and Technology, Dept. of Electr, Eng., 43 Keelung Rd. Sec. 4, Taipei 106 Taiwan ; [2]Brooklyn College of CUNY, Phys. Dept., 2900 Bedford Ave., Brooklyn, NY 11210-2889 USA; [3]UCLA, Dept. of Mats. Sci. and Eng., Los Angles, CA 90095 USA; [4]TRW, Electr. and Tech. Div., Redondo Beach, CA 90278 USA

Using photoreflectance (PR) at 300 K we have characterized the properties of four Ga1-yAlyAs/InxGa1-xAs/GaAs high electron mobility structures with different well width fabricated by molecular beam epitaxy on (100) GaAs substrates. The nominal values of x and y were 0.2. The well width were 140, 160, 160 and 220 Å, respectively. For latter three samples the well width exceeds the pseudomorphic limit so that there is some strain relaxation and related misfit dislocations, as determined from x-ray measurements. In order to detect the anisotropic strain of the misfit dislocations related to strain relaxation, the PR measurements were performed for incident light polarized along [110] and directions. The PR spectra contained signals from the InGaAs single quantum well in addition to the GaAlAs top layer, GaAs and GaAs/GaAlAs multiple quantum well (MQW) buffer layer. Evidence for the influence of the strain relaxation upon the relaxed channel was provided by the observed anisotropy in the InGaAs PR signal for light polarized along [110] and A detailed analyze these features makes it possible to evaluate In and Al compositions, channel width and two-dimensional electron gas density as well as the properties of the GaAs/ GaAlAs MQW buffer layer.

2:10 PM +

Depth Defined Optoelectronic Modulation Spectroscopy: Chi-Hsin Chiu[1]; *John Garth Swanson*[1]; [1]Kings College London, Electr. Eng., Strand, London WC2R 2LS UK

This paper describes how Optoelectronic Modulation Spectroscopy(OEMS) has been adapted to isolate the electrical and optical responses of traps at the interface between an active layer and a buffer layer. OEMS uses periodic photon energy modulation to optically modulate an electrical parameter associated with a semiconductor device structure. The measurand is then displayed as a spectrum as the mean photon energy is scanned. The electrical response may not be in phase with the photon energy variation so that the phase and magnitude spectra can be captured. The method has been used previously in various modes to explore the optical responses of FET's, pn and Schottky diodes as well as simple resistors.(1, 2) Electron traps at the interface between the active layer of a FET and the buffer are of interest because of their role in backgating. The supply of charge from a backgating electrode will vary this trap population, in turn modifying the electric field at the interface with the active layer. In a MESFET this will vary the depletion region near to that interface and modify the channel current. Sub band-gap photons are used to permit penetration into the semiconductor to excite charges in deep defect states. The current in a MESFET is determined by the dimensions of the conductive channel, its carrier concentration and the carrier mobility. The thickness of the channel is set by the thickness of two depletion regions one beneath the gate, the other at the active layer buffer interface. If the photon modulation varies the trap population in any of these regions the channel current will be modulated too. This is the measurand in our experiments. Gate depletion region modulation of the channel current is eliminated by using a closed loop control system to stabilise the gate depletion capacitance continuously throughout the measurement of the OEMS spectrum. This is a crucial process and is fundamental to our measurements. Photomodulation of the gate depletion width

is therefore discounted. We show that photoconductive modulation of the channel itself is negligible in comparison with modulation arising from the back plane traps. Electrons removed from these traps cause the back depletion region to contract increasing the channel current whilst positive charge removal from hole traps has the opposite effect and reverses the phase of the modulation. The method has been applied to GaAs MESFET structures and it is demonstrated that the measurement system is capable of observing changes of back plane charge concentration as small as electrons.

2:30 PM +
Surface Photovoltage Spectroscopy of Two Dimensional Structures and Devices: *Nurit Ashkenasy*[1]; Sanelia Solodky[1]; Mark Leibovitch[2]; Yossi Rosenwaks[1]; Irit Halkon[2]; Yoram Shapira[1]; [1]Tel Aviv University, Dept. of Phys. Electr., Faculty of Eng., Ramat-Aviv, Tel-Aviv 69978 Israel; [2]ELTA Electronics Industries, Ltd., P.O. Box 330, Ashdod 77102 Israel

In this work we have characterized GaAs/AlGaAs single quantum well (QW) p-i-n structures for solar cell applications and InGaAs/GaAs/AlGaAs p-HEMT structures using surface photovoltage spectroscopy (SPS). The spectra obtained are strongly correlated to device performance. Experimental and numerical studies of the photovoltaic response of single quantum well p-i-n structures for solar cell applications will be presented. It is shown that the photovoltaic response is governed by the QW parameters, in particular the dependence on QW width is discussed. Numerical calculations show a monotonic increase in the photovoltaic response with decreasing well width due to the ensuing increase in carrier generation rate and bandgap. The domination of the carrier lifetime in the well over recombination processes throughout the entire structure is discussed. Using a simple empirical model, the carriers effective lifetimes at the well layer/interface for the different samples are estimated. The surface photovoltage spectra of the p-HEMT contain information from different layers of the device. The characterization of the different layers is done by their fingerprints. The composition and quality of the different layers are estimated. In particular, device parameters, such as the channel carrier sheet density, are evaluated. These results show that SPS is a powerful tool for obtaining both optical and electronic characteristics of complicated device structures, and may be used for characterization and quality control of such structures in production lines.

2:50 PM +
UHV Contactless Capacitance-Voltage Characterization of Free Silicon Surfaces: *Toshiyuki Yoshida*[1]; Hideki Hasegawa[1]; Takamasa Sakai[2]; [1]Hokkaido University, Research Center for Interface Quant. Electr. (RCIQE) and Graduate School of Electr. and Info. Eng., Kita-ku, Kita 13 Nishi 8, Sapporo, Hokkaido 060-8628 Japan; [2]Dainippon Screen Manufacturing Co., Ltd., Fushimi-ku Hazukashi, Furukawa-cho 322, Kyouto, Kyouto-hu 612 Japan

Atomic-scale characterization of Si surface properties becomes increasingly important to further advance the Si CMOS technology as well as to develop novel Si-based quantum effect devices. Since the performances of nano-devices are extremely sensitive to electronically active near-surface defects introduced during processing steps, UHV-based in-situ and non-destructive electronic characterization of Si surfaces is strongly required to optimize the processing steps. However, there has been no well-established non-destructive characterization method of surface electronic properties. This paper presents the results of in-situ electronic characterization of free Si surfaces using a contactless UHV capacitance-voltage (C-V) measurement technique. In this technique, a narrow UHV-gap (300-400 nm) is maintained between the electrode and the sample surface by a piezo-mechanism with capacitance feedback from three surrounding parallelism electrodes. This thin gap acts as an additional insulator and allows standard MIS assessment in the UHV environment. The UHV gap length is accurately determined by measuring the variation of reflectance of laser light due to disturbance of the evanescent wave (Goos-Haenchen effect). Unlike conventional MIS measurements, the UHV gap length can be varied in this system. By capacitance measurements changing the gap length, Fermi level pinning position can be determined. This system also connected with the UHV-based multi-chamber growth/fabrication facility for in-situ and non-destructive characterization. As

examples of free silicon surfaces, hydrogen (H)-terminated Si (111) and (100) surfaces were prepared by BHF/NH_4F(40%) and HF/HCl related treatments, respectively. The capacitance for the H-terminated (100) surface showed variation from accumulation down to strong inversion. On the other hand, it was limited well below the accumulation capacitance for (111) surface under strong positive biases, indicating existence of strong surface Fermi level pinning. The distribution of surface state density (D_{it}) for (100) surface was superposition of a wide U-shaped distribution and a narrow discrete peak situated at energy position of 0.65 eV from E_V. For (111) surface, the surface state density showed a narrow U-shaped distribution, where D_{it} rapidly increased toward EC at energy position of 0.6-0.7 eV from E_V. This indicates that the pinning center in the (111) surface is the same discrete defect with the (100) surface, but its density is much higher. After the annealing of H-terminated (100) surface in UHV environment at 300°C for 5 min, the distribution of surface state density showed similar shape, but the height of the discrete peak increased. This indicates that the origin of the discrete state is unterminated surface dangling-bonds whose number increased after escape of hydrogen by annealing. Results on (7x7) reconstructed surfaces and ultrathin insulator covered surfaces will also be discussed. The present technique can detect subtle changes of the surface, and thus is powerful for process optimization in UHV environments.

3:10 PM   Break

3:30 PM +
Far UV Spectroscopic Reflectometry: *S. Lim*[1]; S. Kriventsov[1]; T. Mayer[1]; T. Jackson[1]; J. Freeouf[2]; [1]Penn State University, Center for Thin Film Devices and Electr. Mats. and Processing Research Laboratory, University Park, PA 16802; [2]Interface Studies Inc., Katonah, NY 10536

We have constructed a polarizer-based spectroscopic reflectometry system which operates in the photon energy range 3 eV<hu<9eV. This system uses MgF_2 polarizers and a controlled ambient to eliminate atmospheric oxygen-related optical absorption at short wavelength. The light source is a water cooled lamp, with a MgF_2 window. The system has been primarily operated in the reflection anisotropy spectroscopy mode, in which measurements are made at near-normal incidence, and the signal monitore is the difference in reflection coefficients when the polarization is oriented along different crystallographic directions. This difference should be zero by symmetry for perfect, bulk material, and non-zero results provide information about surface topography (e.g. steps), reconstructions, surface fields, and other departures from bulk symmetry. The high photon energy regime allows wide band gap semiconductor materials to be inverstigated at their critical points. We have used the system to study epitaxial silicon carbide samples and bulk silicon carbide samples with varying surface polish. We have also measured silicon samples; the well known optical response of these samples at more conventional photon energy simplifies system calibration. The system also provides the basic framework required for performing Far UV ellipsometry. We expect that spectroscopic ellipsometry in this energy range will be important not only for wide bandgap semiconductors, but also for ultrathin and/or new dielectrics, and their metrology, and in characterizing materials and coatings for Far UV (for example, 193 or 157 nm) lithography. This work was supported in part by the BMDO Innovative Science and Technology Office and managed by U.S. Army Space and Missile Defense Command.

3:50 PM
Spectroscopic Ellipsometry for Real-Time Control of Heteroepitaxy of HgCdTe on Si: *L. A. Almeida*[1]; Nibir K. Dhar[2]; J. David Benson[3]; Michael Martinka[3]; Andrew J. Stoltz[1]; John H. Dinan[3]; [1]E-OIR Measurements, Inc., P.O. Box 1240, Spotsylvania, VA 22553-1240 USA; [2]Army Research Laboratory, Adelphi, MD; [3]Night Vision & Electronic Sensors Directorate, Fort Belvoir, VA 22060-5806 USA

A technique has been developed to monitor and control precisely (DT ~ 0.2°C) and in real-time, the surface temperature of $Hg_{1-x}Cd_xTe$ as it is deposited by molecular beam epitaxy (MBE). Epitaxy of $Hg_{1-x}Cd_xTe$ has been carried out on (211) Si wafers with buffer layers of Si, ZnTe and CdTe, which were also deposited by MBE. This process was

accomplished entirely in vacuo through the use of a cluster tool with three interconnected MBE systems. The Si wafer surface was terminated with hydrogen atoms ex situ and these atoms were thermally removed in situ. The Si wafers were mounted in indium-free, molybdenum holders. A significant challenge faced in the deposition of $Hg_{1-x}Cd_xTe$ on a CdTe/ZnTe/Si substrate is the dramatic change in emissivity which occurs as the $Hg_{1-x}Cd_xTe$ epilayer is deposited and which causes transients in the substrate surface temperature. This is especially problematic given the narrow window of substrate temperatures (DT ~ 5°C) within which high quality $Hg_{1-x}Cd_xTe$ epilayers can be deposited by MBE. Real-time control of the substrate surface temperature was achieved using spectroscopic ellipsometry. The substrate temperature prior to growth was determined by a previously established library of dielectric functions versus temperature for bulk $Cd_{0.97}Zn_{0.03}Te$ substrates. Despite the difference in composition between the CdTe/Si substrates and the bulk $Cd_{0.97}Zn_{0.03}Te$ substrate, the error in the temperature determination was found to be insignificant. After deposition was initiated, the ellipsometry data was modeled using a previously established library of dielectric functions of $Hg_{1-x}Cd_xTe$ as a function of composition. Due to the temperature dependence of the Hg sticking coefficient, the near-surface composition of the growing epilayer is sensitive to surface temperature. It has been found that a change of 1°C in substrate temperature causes a change in the measured x-value of 0.005. The ellipsometer is sensitive to transients in composition of Dx ~ 0.001, and therefore, capable of detecting transients in substrate temperature DT ~ 0.2°C. Transients in the composition were correlated to changes in surface temperature. Utilizing ellipsometry-generated compositional profiles as a guide, substrate heating power was ramped in such a way as to minimize transients in the measured composition.

4:10 PM
In Situ Controlled Electronic Properties of Low Temperature GaAs(001) for TwO-Photon Absorbers: *J. Herfort*[1]; G. Apostolopoulos[1]; W. Ulrici[1]; L. Däweritz[1]; K. H. Ploog[1]; M. Leitner[2]; P. Glas[2]; [1]Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, D-10117 Berlin Germany; [2]Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie, Rudower Chaussee 6, D-12474 Berlin Germany

The interest in low temperature grown GaAs (LT-GaAs) has increased rapidly due to the unique electrical and optical properties of the material and its wide range of optoelectronic applications. LT-GaAs layers grown by molecular beam epitaxy (MBE) at substrate temperatures between 200ºC and 350ºC exhibit, among other attractive properties, ultrashort carrier lifetimes in the picosecond range and large two photon absorption coefficients. These properties are attributed to the large amount of excess As (»1 at.%) incorporated during growth. The excess As results in a high density (»10^{20} cm^{-3}) of deep traps near midgap, which are responsible for the short recombination times and enhanced optical nonlinearity. In view of tailoring particular material properties, there is a lack of appropriate in situ techniques that probe the properties of LT layers during growth. For LT-GaAs it is known that reflection high-energy electron diffraction (RHEED) yields little information about the growth process. To overcome these limitations we propose to use reflectance-difference spectroscopy (RDS), a technique which is generally considered as a complementary tool for MBE growth. We will demonstrate that RDS can serve as an in situ control tool, probing not only the surface structure but also directly the electronic properties of the growing material. The RD spectra were measured using a commercial spectrometer which is based on the standard design introduced by Aspnes. The recorded signal consists of the real part of the reflectance difference for light polarized parallel to the principal axes [-1 1 0] and [1 1 0], with photon energies between 2 and 5 eV. The strong anisotropic resonances observed around the E_1 and E_1+D_1 critical points are due to the linear electro-optic (LEO) effect [1] caused by the near surface electric field of LT GaAs. The RD spectra can be recorded in situ during growth as well as at growth interruptions. The amplitude of the LEO resonance is sensitive to growth temperature, growth rate and the As_4:Ga beam equivalent pressure ratio, so that it can be used for controlling these parameters. To correlate the information gained from the RDS data with the actual electronic properties of the LT-GaAs layers, which primarily depend on the excess As concentration incorporated during MBE growth, the concentration of the As antisite defects of the layers are estimated by near infrared absorp-

tion measurements. Over a wide range of growth temperature a nearly linear relation between the LEO amplitude and the As antisite concentration is found. Finally, we will demonstrate that the in situ controlled incorporation of excess As during MBE growth can be successfully used to realize and optimize a two-photon absorber for mode-locking of Nd:glass fiber lasers. [1] H. Tanaka, E. Colas, I. Kamiya, D. E. Aspness, R. Bhat; Appl. Phys. Lett. 59 (1991) 3443.

4:30 PM +
Investigation of Indium Surface Segregation in Solid Source MBE Growth of InxGa1-xSb: *David H. Tomich*[1]; Kurt G. Eyink[1]; Steve Fenstemaker[2]; Larry Grazulis[2]; Charles W. Tu[3]; [1]Air Force Research Laboratories, MLPO, 3005 P St. Ste. 6, Bldg. 651, WPAFB, OH 45433-7707 USA; [2]Research Institute, University of Dayton, 300 College Park Dr., Dayton, OH 45469-0167 USA; [3]University of California, San Diego, Dept of Elect. and Comp. Eng., 9500 Gilman Dr., Mail Code 0407, La Jolla, CA 92093-0407 USA

The requirements placed upon infrared detectors have continuously increased in terms of performance, wavelength and operating temperature. Strained layer superlattices (SLSs) in the antimonide system have been receiving considerable attention for use as long and very long wavelength infrared detectors for space based applications. Detectors fashioned from this material system are predicted to have an increased operating temperature and equivalent D* to current Si:As BIB detectors operating at 4 Kelvin. These SLSs are composed of layers of InxGa1-xSb and InAs with periods of approximately 60 A and a composition, x, around 23%. However, the parameter window for growth of high quality heterostructures in this system is significantly narrower than that for the growth of, e.g. GaAs/AlGaAs based structures, partially because of the mixed anion growth and mixing at interfaces. Recently much attention has been given to the interface chemistry due to its affect on the band line up and residual strain present in the SLS. It is known for InGaAs growth that indium segregates to the surface during MBE growth and therefore is expected to occur in this system also. Due to the electrical (band line-ups) and structural (strain) effects surface segregation would have on the SLSs we have examined the affects of substrate growth temperature on indium surface segregation during the growth of various InxGa1-xSb layers on GaSb substrates. We have grown InxGa1-xSb layers with x compositions between 0.13 and 0.34. Desorption mass spectrometry was used to determine the indium concentration. To determine the near surface and surface indium concentration Auger electron spectroscopy (AES) and ion-scattered spectroscopy (ISS) were used respectively. Bulk indium composition was determined by x-ray diffraction measurements on relaxed (thick) InxGa1-xSb layers. Significant indium surface segregation was found to be present after growth. The magnitude and variability with growth temperature and bulk indium composition of the indium surface concentration will be presented. The difference or lack thereof, when using tetramer and dimer/monomer antimony during growth of these samples will also be presented.

4:50 PM
Improved Composition and Layer Interface Control by Modeling Knudsen Cell Heating Cycle: *Stephen J. Adams*[1]; Kurt G. Eyink[1]; [1]Air Force Research Laboratory, AFRL/MLMR Bldg. 653, 2977 P. St., Suite 13, Wright-Patterson AFB, OH 45433-7746 USA

Precise flux control of effusion cells is a central issue for MBE research that effects growth modes, alloy compositions and defects of epitaxial films. Previous research has focused on two aspects of this problem. Namely the elimination of the flux transient present during the opening of the shutter by applying an appropriate temperature schedule to the cell and the development of a close-loop flux control of the knudsen cell after the shutter is opened. While these solutions address the problem of sharp interfaces and constant composition after shutter opening, they do not address the problems which occur with additional cycling of the shutter. When the shutter is closed the cell state changes due its increased heat and begins to progress towards its initial state prior to any opening of the cell. This phenomenon results in a change in the composition to occur with subsequent shutter openings. In this paper we will show that by additionally modeling the heating cycle of a closed shutter it is possible obtain stable flux through multiple opening events.

Session EE. Semiconductor Quantum Dots - Electronic Structures

Friday PM   Room: Corwin West
July 2, 1999   Location: University Center

Session Chairs: Mark Miller, University of Virginia, Dept. of Elect. Eng., Charlottesville, VA USA; Peter Sercel, University of Oregon, Phys. Dept., Eugene, OR USA

1:30 PM
Modified Fermi-Level Pinning of the (100) GaAs Surface Through InAs Quantum Dots in Different Stages of Overgrowth: *Carsten Walther*[1]; H. Niehus[1]; A. Thamm[2]; W. T. Masselink[1]; [1]Humboldt University Berlin, Dept. of Phys., Invalidenstr. 110, Berlin 10115 Germany; [2]Paul-Drude-Institut, Hausvogteiplatz 5-7, Berlin 10117 Germany

This study describes the effect of InAs quantum dots on the Fermi-level pinning at a (001) GaAs surface and uses the Fermi-level pinning energy together with atomic force microscopy to investigate the formation and overgrowth of the dots. room-temperature modulated photoreflectance at van Hoof structures [1] was used to measure the fields and surface pinning in fully depleted GaAs epitaxial layers through Franz-Keldysh oscillations. Observed phase delay data also allows measurement of effective detrapping times from the dots. Our data show that quantum dots with base lengths of between 10 and 25 nm lead to the Fermi level being pinned approximately 250 meV deeper in the bandgap than surfaces without the dots, from 0.65 eV below the conduction band edge for bare GaAs to 0.90 eV with the InAs dots. This effect is opposite to that for thicker two-dimensional InAs and is reversible by either overgrowing the dots with GaAs or by selectively etching away the dots. These results are discussed within the framework of recent theoretical investigations of surface states associated with uncapped quantum dots [2]. The appearance of polar-As surface facets on the dots introduces a large enough density of surface states between the valence band edge and the GaAs surface states to re-pin the Fermi level deeper in the bandgap. Total overgrowth of the dots with GaAs causes these facets to disappear and the Fermi level returns to its position usual for GaAs surfaces. Comparison of the Fermi-level pinning energy with in-air atomic force microscopy images of surfaces with various dot development and overgrowth allows the microscopic surface structure to be characterized by a Fermi-level pinning energy. Studied surface reactions include material transport away from the dots and intermixing in the GaAs barriers as well as depressions of the two-dimensional overgrown GaAs at the positions of the dots. In addition, we use such data to discuss the annealing of the surface with PH_3 which leads to a surface atom exchange and a rearrangement of the InAs due to the modification of the total strain. [1] C. Van Hoof, K. Deneffe, J. DeBoeck, D.J. Arent, and G.Borghs, Appl. Phys. Lett. 54, 608 (1998).[2] T. Saito, J.N. Schulman, and Y. Arakawa, Phys. Rev. B 57, 13016 (1998).

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Tunneling Spectroscopy of Electron States in Self-Assembled InAs Dots: *Kanji Yoh*[1]; Yoshiyuki Kitasho[1]; [1]Hokkaido University, Research Center for Interface Quantum Electronics, N 13, W 8, Kita-ku, Sapporo, Hokkaido 060 Japan

Energy states of confined electrons in self-assembled InAs quantum dots have been investigated so far by various methods such as infrared spectroscopy[1], single electron charging effects[2] capacitance measurements[3], but the measured energy states of those methods were overlapped with the charging energy. On the other hand, direct measurements by ballistic electron spectroscopy has not been reported so far because of the difficulty to probe the bound states of the dots in the GaAs barrier by electron tunneling. We report the direct electron tunneling spectroscopy of bound states of InAs quantum dots buried in a GaAs layer in the vicinity of the GaAs surface. Diamagnetic shift of the ground state of an electron in the dot was clearly observed for the first time. We have fabricated a simple structure burying self-assembled InAs quantum dots 100? below the GaAs surface where thin aluminium layer was evaporated in-situ in order to minimize the introduction of surface states, thereby allowing direct measurements of ballistic electrons to tunnel through bound states in InAs dots. The current voltage characteristics revealed distinct two major peaks suggesting tunneling current through two eigenstates in InAs dots at 2K. The relative peak positions were estimated from the measured peak voltage and energyband shape at each resonant conditions by taking account of the leverage factor 2. The major current peak through the first excited state was found to lie at 55meV below the conduction band minima of GaAs and the ground state was found at 80meV below the first excited state. Line width of the current peaks were found to be 30-35meV which is reasonable if it is compared with FWHM of Å60meV in the photoluminescence data. Several distinct peaks have been observed by analyzing first and second derivative signals. Some of the small peaks are attributed to phonon replica but there are some unidentified peaks yet to be analyzed. When the samples were measured under magnetic field parallel to the current, the peak position is increased reflecting the diamagnetic shift[4] of the relatively large (400Å) quantum dot. Unlike the photoluminescence measurement[5], the present result is unique in investigating not an exciton states but electron states in the dots through direct tunneling current measurements in a magnetic field. REFERENCE [1] M. Fricke, A. Lorke, J. P. Kotthaus, G.Medeiros-Ribeiro and P. M. Petroff, Europhys.Lett.36(3), pp.197-202 (1996) [2] K.Yoh, J. Konda and N. Nishiguchi, Jpn.J. Appl. Phys.77, 3613 (1996) [3] B.T.Miller, W.Hansen, S. Manus, R. J. Ruyken, A. Lorke and J. P. Kotthaus, Phys. Rev.B, 56 (11), pp.6764-6769 (1997) [4] S. Tarucha, D.G. Austing, T. Honda, R. J.van der Hage and L P. Kouwenhoven, Phys. Rev. Lett.77, 3613(1996) [5]I. E. Itskevich, M.Henini, H. A.Carmona, L. Eaves, P. C. Main, D. K. Maude and J. C. Portal, Appl. Phys. Lett. 70 (1997) 505

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Variation of the Potential Well of Self-Assembled InAs/GaAs Quantum Dots with Fixed Ground State Luminescence Energy: *Markus Arzberger*[1]; Ulrich Käsberger[1]; Liwen Chu[1]; Gerhard Böhm[1]; Markus-Christian Amann[1]; Gerhard Abstreiter[1]; [1]Walter Schottky Institut, Am Coulombwall, Garching D-85748 Germany

The direct growth of nanometer-scale quantum dots (QDs) in lattice mismatched systems via the Stranski-Krastanow epitaxial growth mode is a suitable method for fabrication of quantum effect devices like QD lasers or optical memories. We studied in detail the dependence of the InAs island growth on GaAs (001) by MBE at substrate temperatures (T_S) of 480°C and 530°C using photoluminescence (PL) and atomic force microscopy (AFM) for characterization with respect to PL intensity, PL energy and density of the islands. Buried InAs islands produced by depositing ~2.8 monolayers (MLs) of InAs at T_S=530°C and an arsenic (As_4) equivalent pressure (p_{As}) of ~1.2×10^{-5} Torr have the PL ground state transition at ~0.99 eV (room-temperature, RT) with full width at half maximum (FWHM) of about 38 meV, showing good homogeneity of the QDs. The density and height of these islands is ~1.5×10^{10} cm^{-2} and 9-10 nm, respectively, both determined by AFM measurements performed on unburied islands in ambient air. We increased the density of the islands by means of a lower growth temperature and a correspondingly lower surface mobility of adatoms during growth. We achieved densities in the range of ~1×10^{11} cm^{-2} (height 3-4 nm) by depositing ~2.7 MLs InAs. The RT PL intensity of these low temperature grown QDs is very sensitive to p_{As} and can be increased by decreasing p_{As} to 2-3× 10^{-6} Torr. If ~4 MLs InAs are deposited at T_S=480°C the ground state transition appears also at ~0.99 eV with an FWHM of about 35 meV, both very similar to the QDs grown at T_S=530°C (2.8 MLs). The density and height of these QDs is ~5×10^{10} cm^{-2} and 5-6 nm, respectively. Comparing the power dependence of the PL of these QDs at 480°C and 530°C we observe an energy spacing of the ground and first excited state of ~81 meV (480°C) and ~66 meV

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(530°C), although the ground state is at the same energy for both samples. This is explained by more effective interdiffusion of In and Ga atoms during growth at 530°C leading to more Ga containing QDs as at 480°C. This means that the carriers are confined in deeper but narrower potential wells in the 480°C QDs than in the 530°C QDs. As the ground state for both kinds of QDs has the same energy, the first excited state is shifted to higher energies in the 480°C QDs as compared to the 530°C QDs. Therefore the density and the interlevel spacing of InAs QDs can be tuned by varying the substrate temperature without changing the ground state energy.

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Electrical Detection of Optically Induced Charge Storage in Self-Assembled InAs Quantum Dots: *Doris Heinrich*[1]; Matthias Skalitz[1]; Jonathan Finley[1]; Jan Hoffmann[1]; Artur Zrenner[1]; Gerhard Bohm[1]; Gerhard Abstreiter[1]; [1]Walter Schottky Institut, Technical University Munich, Am Coulombwall, D-85748 Garching Germany

We report about a spectrally resolved photo-resistance study of optically induced charge storage effects in self-organized InAs quantum dots (QDs). The results show that optical QD charging with spectral resolution can be detected and erased electrically. This provides a novel electrical technique by which QD excitation spectra can be studied. The investigated structure designed for electron storage in the QDs consists of a modulation doped 2D electron channel which was grown on top of a layer of InAs QDs, separated by an asymmetric tunnel barrier. In this structure the QDs are incorporated into the intrinsic region of a vertical p-i-n heterojunction with separate ohmic contacts to the 2D electron channel and the back p-contact. As a consequence of the vertical built-in field in the p-i-n junction, photo-excited holes escape from the QDs drifting to the p-contact, while the electrons remain stored in the QDs. Photoluminescence reveals ground (E_0 at about 1 eV) and excited state (E_1 and E_2) QD-emission with a level spacing of 60 ± 2 meV. For resonant excitation close to the ground state electron storage can be obtained in a specific subset of QDs. This results in a large increase of the lateral resistance ($DR/R = 20-100$ %) of the remote 2D n-channel. The spectral dependence of the storage effect ($DR(E)/R$) was investigated by repeatedly charging and erasing (by electrically injecting holes into the QD layer from the p-contact) the QD ensemble for excitation energies E_{ex} from below E_0 to beyond E_2. Resonances are observed in the spectral variation of DR/R, the most pronounced of which arise at energies of 33 ± 5 meV, 110 ± 10 meV and 175 ± 10 meV above E_0 respectively. Similar resonances are observed in the QD charging rate. We suggest that the resonances arise from inelastic excitation of QD states, which lie at odd multiples of the LO-phonon energy below E_{ex} and suggest, that the even phonon satellites are absent since the $E_0 - E_1$ energy separation is resonant with twice the LO-phonon energy. This photo effect is persistent over time scales longer than 8 hours at 140K. A reference structure without QD layer did not reveal a similar storage effect. Analogous structures designed to store holes in the QD layer show memory effects similar to the electron storage structure.

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Dark Excitons Due to Direct Coulomb Interactions in Silicon Quantum Dots: *Fernando A. Reboredo*[1]; Alberto Franceschetti[1]; Alex Zunger[1]; [1]National Renewable Energy Laboratory, Solid State Theory, 1617 Cole Blvd., Golden, CO 80401

Much of the interest in semiconductor quantum dots centers around the ability to tune their emission energy and intensity via their quantum size. For that purpose, it is desirable to have allowed excitonic transitions. However, it is possible that quantum size effects will make the lowest exciton forbidden ("dark"). The first such case is due to electron-hole exchange effects in dots made of a direct-gap Zinc-Blende material. In this case, in spherical quantum dots, the valence band maximum (VBM) has t_2 symmetry while the conduction band minimum (CBM) is a_1. Consequently, the electron-hole exciton is $t_2 \times a_1 = T_2$ which is optically allowed. However, the electron-hole exchange can split T_2 into a lower energy triplet and a higher energy singlet. Therefore, for direct gap quantum dots the only possibility to have a forbidden "dark exciton" is the exchange splitting which raises the energy of the allowed singlet state as compared to the forbidden triplet states. This has been observed in CdSe and InP by comparing PL with PLE. The second case explored here is when the bulk material from which the QD is made

is a multi-valley semiconductor. In the particular case of Si, the symmetry of (VBM) is almost always t_2. However, for indirect gap systems, the symmetry of the CBM is in many cases different from a_1 for example e or t_2. In these cases, the resulting lower energy exciton has several symmetries (e.g. $t_2 \times t_2 = A_1 + E + T_1 + T_2$ or $t_2 \times e = T_1 + T_2$). Only T_2 is optically active, the others are "dark". Using pseudopotential calculations of the single-particle states of Si quantum dots and a direct evaluation of the screened e-h Coulomb and exchange matrix elements, we find that, when the CBM symmetry is t_2, the e-h direct Coulomb interaction lowers the energy of the non-T_2 states that are called dark excitons. Thus, the lowest energy exciton is forbidden even without exchange interaction. At very low temperatures (T <20 K) the emission will be long-lived and weak. To get strong emission it is required to populate the T_2 singlet exciton. That can be done at temperatures larger than 20 K. In addition, in contradiction with simplified models, we find that Coulomb correlations are more important for small dots than for intermediate size ones.

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Photoluminescence of Strain-Induced Coupled Quantum Dot-Pairs: *H.-W. Ren*[1]; T. Okuno[2]; K. Nishibayashi[2]; J.-S. Lee[1]; S. Sugou[1]; M. Sugisaki[1]; Y. Masumoto[1]; [1]Single Quantum Dot Project, ERATO, JST, c/o NEC Corporation, 34 Miyukigaoka, Tsukuba 305-8501 Japan; [2]University of Tsukuba, Institute of Phys., Tsukuba 305-8571 Japan

Fabrication and identification of electronically coupled quantum dots (CQDs) is still a challenging issue for physicists. Researches have been carried out by three-step growth and cleavage processes (1) and also by stacking self-assembled quantum dots aligned along the growth direction (2). We propose a simple method to fabricate CQDs by growing self-assembled InP islands as stressors on the InGaAs/GaAs and GaAs/AlGaAs coupled quantum wells (CQWs). The stressor, which is a nanometer size island with larger lattice constant, produces a quasi-parabolic laterally confined potential profile (3) in the vertically CQWs, hereafter called strain-induced CQDs. Samples were fabricated on GaAs (001) in an EMCORE D-75 MOVPE system with high reproducibility. The InP islands with 4ML nominal supply formed on GaAs at 600°C are highly uniform and faceted with 45nm base diameter and 14nm height. Since the stressor induced strain field decays almost exponentially with a characteristic penetration depth of about 30nm, QDs formed in the upper and lower QWs are not identical so that the QD-pairs are asymmetrically coupled. Even though, coupling gives rise to reductions of the QD state energies. If the QD state in the upper QW matches one in the lower QW, resonance occurs so the bonding and anti-bonding states will be formed. For strain-induced In0.135Ga0.865As/GaAs CQDs with a 3.3nm GaAs cap and two 3.8nm QWs, by adjusting the spacer layer thickness between the two QWs, the alignment of the quantum states between the two dots is tuned. The resulted QD states are resolved through state filling in the photoluminescence spectra at various excitation intensities. In addition, quantum states in the GaAs/Al0.3Ga0.7As CQDs with 2.4nm GaAs/9nm Al0.3Ga0.7As caplayers, two 4.8nm QWs with 2nm spacer are also investigated by changing the width of one of the QWs. The number of confined QD states below the ground state of CQWs, their energies, half-widths and peak intensities are used to analyze the coupling strength between the dot-pairs. (1). G. Schedelbeck, et.al. Sci., 278 (1997) 1792. (2). R. Heitz, et.al. Phys. Rev. B 58 (1998) R10151.(3). H. Lipsanen, et. al. Phys. Rev. B 51 (1995) 13868.

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Experimental Determination of Intra-level Relaxation Time in Quantum Dots with Different Energy Level Spacing: *H. Koskenvaara*[1]; M. Sopanen[1]; H. Lipsanen[1]; M. Brasken[2]; M. Lindberg[2]; [1]Helsinki University of Technology, Optoelectronics Laboratory, Espoo FIN-02150 Finland; [2]Abo Akademi University, Dept. of Phys., Turku FIN-20500 Finland

Quantum dots (QD's) induced by self-assembled stressors, especially InP islands, have demonstrated excellent luminescence efficiency and narrow transition peaks even from an ensemble of QD's. Therefore, this structure offers good possibilities to study the relaxation and recombination processes occurring in QD's, because up to seven distinct

QD levels can be probed. In this paper we report the experimental determination of recombination and relaxation times of stressor-induced QD's having different energy level spacing. Two theoretical models are used to analyze the data and to discuss the origin of the observed trends in the measurements. The stressor-induced QD samples were fabricated by metalorganic vapor phase epitaxy on (100) GaAs substrates. The structure consists of a single near-surface Ga[0.8]In[0.2]As/GaAs quantum well (QW) having a QW thickness of 8 nm and a top barrier thickness of 5 nm on top of which self-assembled InP islands were grown. Five samples having a similar QW structure but with a different growth temperature (610 to 665°C) for the islands were fabricated. Therefore, the InP islands have a different average size in each sample. The average island height and diameter increase with increasing growth temperature. Therefore, the potential induced by a larger stressor becomes deeper, but also wider, resulting in reduced energy level spacing. The samples were characterized by low-temperature photoluminescence (PL) and time-resolved PL measurements. The time-resolved data was analyzed using two different theoretical models. The relaxation and recombination time constants were determined using a simple rate-equation model. The recombination and relaxation times were observed to increase from 1.3 ns and 0.2ns to 2.0 ns and 2.0 ns, respectively, when the energy level spacing decreased from 25.0 meV to 13.5 meV. The time-resolved data measured at different temperatures, i.e., 14-50 K, shows that the recombination time increases with increasing temperature. The relaxation time also increases typically by a factor of two within the same temperature range. Therefore, the dominant relaxation mechanism seems not to be mediated by acoustic phonons. In a recent paper, (M. Brasken et al., Phys. Rev. B 58, R15993 (1998)] a master equation model for electrons and thermal hole population with an Auger-like process where holes are depleted from the QD was shown to explain the observed temperature dependency. With decreasing hole level spacing, the number of holes excited thermally to higher QD levels is increased. Therefore, the apparent recombination time, i.e., the time determined from the rate-equation model, is increased.

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Band Structure Modification of InP Dots at High Pressure: *Linshi Miao*[1]; Dinesh Patel[1]; Carmen S. Menoni[1]; Olga I. Micic[2]; Arthur J. Nozik[2]; [1]Colorado State University, Elect. and Comp. Eng., Fort Collins, CO 80523-1373 USA; [2], National Renewable Energy Laboratory, Golden, CO 80401 USA

We show that in InP quantum dots (QD), the separation between the direct (G_{1c}) and indirect (X_{1c}) extrema is significantly decreased with respect to that of bulk InP, and varies non-monotonically with dot size. Our experiments also show that intervalley G-X mixing is considerably enhanced in the QDs. These characteristics of the electronic band structure of InP QDs were identified from the shift of the photoluminescence (PL) peak with hydrostatic pressure at low temperatures. The InP QD samples of dot sizes 3.2nm, 3.5nm and 5.6nm respectively were prepared by colloidal chemistry and their surface states were passivated with dilute HF solution to improve the emission efficiency [1]. The QDs exhibited strong PL with full width half maximum of 200 meV which reflects a dot size distribution of ±10%. Analysis of the PL peak shift with pressure shows a linear behavior up to about 3GPa. Above 3GPa the PL peak energy varies sublinearly with pressure in all three samples up to about ~ 6 GPa where the PL signal disappears. In contrast, the PL peak energy from bulk InP, which is pressurized simultaneously with the QDs, shows a linear behavior to 6GPa. The QD integrated PL intensity is almost constant up to about 2GPa and rapidly decreases at higher pressures, reaching at 6GPa a value 10^{-2} of its initial atmospheric pressure value. Using a simulation model that takes into account the dot size distribution, the size-dependent G-X separation and G-X intervalley mixing near crossover we calculated the PL spectra at different pressures. The PL peak and integrated intensity variation with pressure were determined from the simulated PL spectra and were fitted to the experimental data. The fit of the integrated intensity shows that the G-X crossover in the QD occurs between 5-6GPa depending on dot size, a transition pressure considerably lower than that of bulk InP. From the crossover pressure and using measured values of the pressure rate of change of the G and X bands, G-X separations of 0.604±0.02eV, 0.591±0.02eV and 0.660±0.02eV were calculated for

3.2nm, 3.5nm and 5.6nm QD respectively. The fit of the PL peak shift with pressure shows that the sublinear behavior at high pressures results from large intervalley G-X mixing, and yields values of the intervalley mixing potential ranging from 65 to 9 0meV for QD size ranging from 5.6 to 3.2nm. The results of our experiments are in very good agreement with recent theoretical predictions of quantum size effects on the G-X transition in InP QD [2]. CSM acknowledges the support of the National Sci. Foundation, CAREER Award ECS-9502888; AJN and OIM were supported by the U.S. Dept. of Energy, Office of Basic Energy Sciences, Chem. Sciences Div.. [1] O. I. Micic, J. Sprague, Z. Lu, and A J. Nozik, Appl. Phys. Letts., vol. 68, 3150 (1996). [2] H. Fu and A. Zunger, Phys. Rev. Lett. vol. 80, 5397 (1997).

Session FF. Issues of Dopants and Defects in Nitrides

Friday PM   Room: Lotte Lehman Hall
July 2, 1999   Location: Music Building

Session Chairs: Christian Wetzel, Meijo University, High Tech Research Center, Tempaku-ku, Nagoya Japan; Alan Wright, Sandia National Laboratoires, Albuquerque, NM USA

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Influence of Dislocations in InGaN/GaN Quantum Well Grown by Metalorgaic Chemical Vapor Deposition: *Tomoya Sugahara*[1]; P. G. Eliseev[1]; Hisayuki Saeki[1]; Maosheng Hao[1]; Tao Wang[1]; Yoshiki Naoi[1]; Katsushi Nishino[1]; Shiro Sakai[1]; [1]The University of Tokushima, Sakai Laboratry Dept. of Elect. and Electr. Eng., 2-1 Minami-Josanjima, Tokushima 770-8506 Japan

Although nitride based devices with high density of dislocations have been developed and commercialized, the dislocations effects are still not clear. So far, we demonstrated that dislocations in GaN act as non-radiative recombination centers [1], and also InGaN phase separation is promoted by dislocations with the screw component when InGaN is thick [2] Moreover, anomalous temperature dependent photoluminescence peak shift was observed in the dislocated InGaN materials with and without phase separation.[3] In this paper we investigated the influence of dislocations in both heteroepitaxial and homoepitaxial InGaN/GaN quantum well structures grown by metalorganic chemical vapor deposition method on sapphire and bulk GaN substrates, respectively. First, the effects of dislocations on the growth and emission processes in InGaN alloys were discussed by means of cathodoluminescence (CL), transmission electron microscopy (TEM), and atomic force microscopy (AFM). The cross-sectional CL images of the sample grown at low temperature in heteroepitaxial InGaN showed that the indium composition in the dislocated area is always higher than in the dislocation-free area. Also, it was found that there is a similarity between the pair of CL dark spots located in the emission area with high indium content and the small pair of pits connected by an atomic step line. These results evidence that dislocations with the screw component favors the formation of In-rich regions. The extra combination of the dangling bond in dislocated areas can prevent the evaporation of InN during the InGaN growth. On the other hand, the CL emission pattern of homoepitaxial InGaN showed uniform emission with no dark spots. Next, the behavior of temperature dependent photoluminescence (PL) peak shift was studied. The anomalous temperature dependent PL peak shift (blue shift and S-shape behavior) was observed in heteroepitaxial InGaN alloy materials, but not in homoepitaxial materials. The temperature-induced anomaly is explained in terms of the band-tail effect[4] produced by the composition variation in the InGaN alloy. Therefore, we conclude, that the composition variations are closely associated with high density of dislocations. We found that the density of states distribution parameters can be corre-

lated with an averaged indium composition in the heteroepitaxial InGaN alloy. References [1] T.Sugahara, H.Sato, M.Hao, Y.Naoi, S.Kurai, S.Tottori, K. Yamashita, K. Nishino, L.T.Romano and S.Sakai: Jpn.J.Appl.Phys.37 (1998) L398; [2] H.Sato, T.Sugahara, Y.Naoi and S.Sakai: Jpn.J.Appl.Phys.37 (1998) 2013; [3] M.Osinski, P.G.Eliseev, P.Perlin, J.Lee, H.Sato, T.Sugahara, Y.Naoi and S.Sakai: Conference on Lasers and Electro-Optics, San Francisco, CA, 3-8 May, 1998; [4] P.G.Eliseev, P.Perlin, J.Lee and M.Osinski, Appl.Phys.Lett.71(5), 569.

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Atomic Scale Analysis of Defect Structures and Properties in III-Nitride Materials by Z-Contrast Imaging and EELS in STEM: *Yan Xin*[1]; Nigel D. Browning[1]; Steve J. Pennycook[2]; Siva Sivananthan[1]; Robert Sporken[3]; F. Omnés[4]; B. Beaumont[4]; J. P. Faurie Faurie[4]; Pierre Gibart[4]; [1]University of Illinois at Chicago, Phys., 845 W Taylor St., Chicago, IL 60607 USA; [2]Oak Ridge National Laboratory, Solid State Div., Oak Ridge, TN 37831 USA; [3]Facultes Facultes Universitaires Notre-Dame de La Paix, Laborotoire L.I.S.E Belgium; [4]CRHEA-CNRS, rue Bernard Gregory, 06560 Valbonne France

Correlated Z-contrast imaging and electron energy loss spectroscopy (EELS) in the scanning transmission electron microscope (STEM) allows the structure, composition and local electronic properties of defects to be quantified with atomic resolution and sensitivity. For nitride materials, where the exact contribution of defects is not yet fully understood, such analysis can provide the fundamental first step in understanding their effect on both the material and subsequent device properties. Using the atomic resolution Z-contrast imaging technique, we unambiguously identify the atomic structure of stacking faults and threading dislocations of pure edge, mixed and of pure screw character. We show that the projected structure of all dislocation cores along the c-axis containing an edge component consist of an 8-fold ring at the core. Additionally, pure screw dislocations are shown to contain a full core. Other defects, such as the prismatic stacking fault, are observed to consist of 4-fold and 8-fold rings. In addition, we extend our work on defects in III-Nitrides by using EELS to measure the effect that each of these atomic structures has on the local electronic properties. In particular, results will be presented from nominally undoped, As doped and Si doped samples grown by MOCVD or MOVPE, as well as from dislocation cores in ELOG samples after the threading dislocations have propagated laterally over the masks. Furthermore, the studies of the interfaces are performed on the MBE grown AlG aN/AlN/Si(111) samples. It has been shown that AlN nucleated on (7x7) reconstructed Si(111) makes a better substrate for the later epitaxial growth of GaN films. It will be shown here that the interfacial microstructures of the AlN/Si and AlGaN/AlN interfaces by atomic resolution Z-contrast imaging provides unambiguously information on the atomic arrangement of the planes at the interfaces.

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Investigation of the Formation of the 2.8eV PL Band in p-type GaN: *Fatemeh Shahedipour*[1]; Bruce W. Wessels[1]; [1]Northwestern University, Mats. Sci. and Eng., 2225 N. Campus Dr., Evanston, IL 60208

In p-type epitaxial GaN, strong photoluminescence is observed at 2.8eV (blue band). This luminescence emerges upon doping with Mg to concentrations in excess of 1×10^{19} cm^{-3}. The origin of the luminescence is controversial although recent studies have indicated that it involves donor-acceptor (D-A) pairs. The acceptor is attributed to Mg_{Ga} center. The donor involves a deep center, which has been tentatively attributed to a nitrogen vacancy complex. In this study the formation of the blue band in heavily Mg doped GaN prepared by MOVPE was investigated. P-type epitaxial layers were annealed at temperatures ranging from 650°C to 750°C. Prior to annealing the Mg related emission band at 3.2eV predominates. Upon annealing in nitrogen the blue band emerges and the resistivity decreases. The intensity of the 2.8eV band depends upon annealing conditions. For the lowest resistivity material the blue band predominates. The emergence of the blue band is associated with the formation of deep donors. The observed annealing behavior is consistent with a proposed model whereby the deep donor involves a nitrogen vacancy complex formed through self-compensation.

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Effect of Threading Dislocations, Mg-Doping and Etching on the Photoconductivity Spectra of GaN: *John T. Torvik*[1]; J. I. Pankove[1]; S. Nakamura[2]; I. Grzegory[3]; S. Porowski[3]; [1]Astralux, Inc., 2500 Central Ave., Boulder, CO 80301 USA; [2]Nichia Chemical Ind., R&D Dept., 491 Oka Kaminaka, Anan, Tokushima 774 Japan; [3]Polish Academy of Sciences, High Pressure Research Center, Sokolowska 29/37, 01-42, Warsaw Poland

The III-V nitrides are prime candidates for solar-blind UV photodetection and operation in harsh environments due to their large bandgap energy, radiation hardness and chemical inertness. However, GaN-based p-n and p-i-n photodiodes grown on sapphire substrates often exhibit broad spectral cutoffs, poor visible rejection and low quantum efficiencies when illuminated through a p-type contact/window layer. This poor performance can largely be attributed to poor p-type doping technology and threading dislocations in the GaN. In this study, we use photoconductivity (PC) spectroscopy to investigate the effects of: 1) threading dislocations, 2) heavy Mg-doping, and 3) etching on the spectral responsivity and expected quantum efficiency in GaN-based UV photodetectors. The GaN-based photoconductive detectors are based on both co-planar and interdigitated finger geometries. In anticipation of the future availability of large-area defect-free GaN for detector applications we compare the photoconductive response of a variety of GaN samples. The samples consist of: 1) heavily Mg-compensated bulk GaN grown under high temperature and pressure, 2) free-standing 100-um-thick unintentionally doped GaN grown by epitaxial lateral overgrowth and MOCVD, and 3) conventional Mg and Si-doped GaN thin films grown on sapphire substrates. Highly resistive bulk GaN:Mg nearly free of threading dislocations has more than 1000 times better visible rejection ratio between 360 nm to 450 nm compared to highly dislocated and comparably doped p-type and n-type GaN thin films grown on sapphire substrates. However, the heavy Mg- and Si-compensation in both the bulk and MOCVD-grown GaN causes a broad spectral cutoff. Unintentionally doped semi-insulating GaN with low dislocation density has a similar rejection ratio compared to the bulk GaN:Mg, but much sharper spectral cutoff due to lower impurity concentrations. Furthermore, post-growth processing steps such as etching and polishing significantly increase the surface recombination compared to the as-grown surface. The results will be discussed with emphasis on GaN-based photodiode design.

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Optically Detected Magnetic Resonance Study of Defects in Undoped, Be-doped, and Mg-doped GaN: *Friedrich Karl Koschnick*[1]; Karsten Michael[1]; Johann Martin Spaeth[1]; Bernard Beaumont[2]; Pierre Gibart[2]; Enrique Calleja[3]; Elias Munoz[3]; [1]University of Paderborn, Phys. Dept., Warburger Str. 100, Paderborn 33098 Germany; [2]CRHEA-CNRS, Valbonne France; [3]University of Madrid, Madrid Spain

Undoped, Be-doped, and Mg-doped GaN samples were investigated with photoluminescence-detected electron paramagnetic resonance (PL-EPR) and electron-nuclear double resonance (PL-ENDOR). The undoped and Mg-doped samples were grown with MOVPE on sapphire. The Be-doped samples were grown with MBE on silicon. In undoped GaN PL-EPR/ENDOR was measured via the yellow luminescence, in Mg-doped GaN PL-EPR/ENDOR was measured via the deep blue Mg-related luminescence, and in Be-doped GaN the measurements were performed via the deep green Be-related luminescence. We found two PL-EPR signals in Be-doped GaN which we assigned to shallow donors and one signal which is probably due to deep Be-related complexes. One type of shallow donors is probably due to Si impurities because of a contamination by the Si substrate. The origin of the other shallow donor is not clear. Impurities others than the dopant Be and the substrate material Si are not expected to be present in a concentration which is measurable with PL-EPR. Therefore, oxygen as an impurity can be excluded. It is possible that the second donor is an intrinsic defect. PL-ENDOR was measured via the PL-EPR lines of the donors in all samples. The observed ENDOR lines were analyzed to be due to distant gallium neighbors, which are located far away from the investigated defect, so that hyperfine interactions cannot be observed. The measured distant gallium ENDOR lines were split by a quadrupole interaction. We determined the electrical field gradients (efg's) at the Ga nuclei in all investigated samples very precisely from the measured quadrupole interac-

tion. Surprisingly, the efg's in the investigated samples are similar and very close to that measured by MAS-NMR on GaN powder. The efg's are very sensitive to strain. We estimated that the strain ezz of the investigated samples is probably smaller than 2×10^{-4} in contrast to values from elsewhere in MOCVD GaN layers [1]. [1] E. R. Glaser, T. A. Kennedy, W. E. Carlos, J. A. Freitas, Jr., A. E. Wickenden, and D. D. Koleske, Phys. Rev. B 57, 8957 (1998)

3:10 PM Break

3:30 PM
Optical Properties of Rare Earth Doped GaN Grown by MBE:

Andrew J. Steckl[1]; [1]University of Cincinnati, ECE/CS Dept., P.O. Box 210030, 899 Rhodes Hall, Cincinnati, OH 45221-0030 USA

We report on breakthroughs made with the incorporation of rare earth (RE) elements into GaN films and resulting light emitting devices. GaN, being a wide bandgap semiconductor, has been shown to minimize the attenuation in near-infrared (IR) emission from the lowest excited state in the RE species for which it is a host (for ex. Er at 1.5 μm, Pr at 1.3 μm). We have obtained for the first time emission from higher excited RE states in GaN, resulting for example in light emission in the green (Er at 537, 558 nm) and red (Pr at 648, 650 nm) regions of the visible light spectrum. This emission is suprisingly strong, being observable with the naked eye at room-temperature. GaN films were grown by MBE with a Ga elemental source and a nitrogen plasma source. RE species were introduced in-situ during growth (from elemental solid sources) on sapphire, Si and thick GaN film substrates. We describe the properties of the RE-doped GaN films, concentrating on the effects of temperature (of the substrate, Ga and RE cells) on the RE incorporation and related photoluminescence (PL) characteristics. The visible PL intensity was found to track very closely the Er concentration introduced during growth. We have fabricated RE-doped GaN light emitting devices utilizing rectifying contacts made with highly transparent and conducting In-Sn oxide. The resulting electroluminescence (EL) is also visible at room-temperature and its spectrum is very similar to the PL spectrum. A linear dependence between EL and bias current is observed.

3:50 PM
Near-Surface Cathodoluminescence Spectroscopy of Erbium Doped AlN:

Alexander P. Young[1]; Stephen H. Goss[2]; Leonard J. Brillson[1]; J. D. MacKenzie[3]; C. R. Abernathy[3]; [1]Ohio State University, Elect. Eng., 205 Dreese Laboratory, 2015 Neil Ave., Columbus, OH 43210-1272 USA; [2]Ohio State University, Center for Materials Research, 205 Dreese Laboratory, 2015 Neil Ave., Columbus, OH 43210-1272 USA; [3]University of Florida, Mats. Sci. and Eng., Gainesville, FL 32611 USA

Erbium doped semiconductors are of significant interest as a potential source of electrically pumped optical emission at 1.55 mm (0.80 eV) for long distance optical communications and other optoelectronic applications. Recently, high quality III-N films with higher bandgaps and low thermal quenching effects have been grown, and it been demonstrated that AlN can serve as a host for Er^{3+} 0.805 eV emission. However, complex interactions affecting emission between the Er ion, the host lattice, C, and O impurities remain to be resolved in order to maximize optical emission. We have investigated the optical activity of Er^{3+} ions in AlN via depth-resolved, low energy (0.75-4.0 kV), cathodoluminescence spectroscopy (CLS) and compared it with the luminescence of AlN without Er. At these energies, the electron beam penetrates roughly from 10 nm to 160 nm into the specimen, therefore we are able to resolve luminescence from the near surface as well as the bulk of the films. The ~1 mm AlN films were grown by MOMBE at 700°C on Al_2O_3 substrates. Dimethylethylamine alane (DMEAA) was used as the source for aluminum in these films, while the nitrogen was supplied via an electron cyclotron resonance plasma source. The Er was supplied by a high temperature effusion cell. Previous measurements by secondary ion mass spectroscopy (SIMS) have shown the AlN doped with Er at a concentration of 3×10^{21} cm^{-3}, while the oxygen content in the films was in the range 10^{20} cm^{-3} and distributed uniformly throughout the film. Room-temperature CLS measurements were performed over a wide spectral range, 0.7- 6.0 eV. We found strong emission in the Er doped films from the first excited->ground state transi-

tion of Er^{3+} at 0.80 eV along with many other excited state transitions. The intensities were five to ten times stronger than luminescence from GaN:Er grown by MOMBE. Furthermore, as the e-beam penetrated into the bulk, the emission from the Er - related features decreased by a factor of two, in contrast with our results on GaN where the luminescence increases toward the bulk region. The features are also significantly broader than for the GaN:Er case, with the two excited state peaks at 2.2 and 2.3 eV now merged into one unresolved feature. In contrast to the AlN:Er film, there was no emission in the IR from the AlN control specimen at any depth, and at higher energies we measured only a broad, weak feature between 1.7-3.25 eV along with an oxygen defect related feature at 3.8 eV, which is significantly enhanced toward the surface. The added O near surface emission combined with the enhanced luminescence from AlN:Er near the surface suggests a role for O in activating the Er. In summary, the large bandgap of AlN is shown to be a major positive influence on Er related luminescence, displaying intense 0.80 eV and higher energy emission. Semiconductor structures incorporating such AlN:Er layers show great promise for future optoelectronic applications. 1. J.D. Mackenzie, C.R. Abernathy,S. J. Pearton, U. Hömmerich, X. Wu, R.N. Schwartz, R.G. Wilson and J.M Zavada, Appl. Phys. Lett. 69, 2083 (1996). 2. X. Wu, U. Hömmerich, J.D. Mackenzie, C.R. Abernathy, S. J. Pearton, R.N. Schwartz, R.G. Wilson and J.M Zavada, Appl. Phys. Lett. 70, 2126 (1997).This work was supported by the DOE under Grant # DE-FG0297ER5666.

4:10 PM
Isoelectronic Doping of Gallium Nitride with Arsenic:

Peter H. Mitev[1]; M. Gherasimova[1]; B. Gaffey[1]; L. J. Guido[1]; [1]Yale University, Center For Microelect. Mats. and Struc., P.O. Box 208284, New Haven, CT 06520-8284 USA

We have previously shown that doping with arsenic dramatically improves the electronic and optical properties of GaN thin films. Now we present new evidence that shows that incorporation of arsenic in an MOCVD-grown GaN has a two-fold impact on the resulting material. First, arsine acts as a surfactant during crystal growth increasing the grain size and improving the surface morphology of the thin films. Second, arsenic atoms are active impurities that change the stoichiometry of the crystal with a beneficial effect on its electronic and optical properties. Two-micron thick GaN:As thin films on c-plane sapphire were synthesized in a horizontal flow MOCVD reactor using TMG, ammonia, and arsine. The epitaxial layer was deposited at 1030°C following a 250 Å buffer layer grown at 550°C. The arsine-to-ammonia vapor pressure ratio was varied between 0.001 and 0.1 with a total ambient pressure of 100 Torr. SIMS measurements show a square-root power law dependence of the arsenic concentration on the arsine flow that reaches 2×10^{17} cm^{-3} in the higher limit with a corresponding increase of the residual silicon concentration from 2×10^{16} cm^{-3} to 8×10^{16} cm^{-3}. The increased grain size is directly evidenced by high-resolution X-ray measurements. As an indirect evidence all GaN:As samples exhibit a two-fold increase of the Hall mobility at room-temperature to 490-620 cm2/V-s from 250 cm2/V-s for undoped GaN. The free electron concentration is relatively constant (n=5-7x1016 cmcm^{-3}) except for the highest-doped sample: n=4.7×10^{17} cm^{-3} for [As]=2×10^{17} cm^{-3}. Such increase can only be explained by a change in the stoichiometry of the crystal since this value exceeds the concentrations of arsenic and silicon together. Measurements of the absolute radiative efficiencies of the individual optical transitions were performed using a calibrated photoluminescence set-up. Several trends are directly correlated to the arsenic concentration. A reduced nonradiative recombination is evidenced by the fact that the efficiency of the band edge emission increases both absolutely and relative to the free carrier concentration. Following an initial increase, the donor-to-acceptor pair transition at 3.3 eV saturates after overcoming the yellow band in the sample with [As]=6.5×10^{16} cm^{-3}. This trend is explained by the competition between the yellow band and donor-to-acceptor transitions assuming that both involve the same shallow donor level. Low temperature spectra show that the emission associated with the neutral-donor-bound exciton is directly proportional to the arsenic content. In addition, a new transition at 2.6 eV appears in the highest doped sample reminiscent of the arsenic signature luminescence prevalent in GaN ion-implanted with arsenic. Although the trends in the electronic properties of GaN:As are similar to what we observed for GaN doped with silicon several

optical trends are diametrically opposite: the radiative efficiency of the band edge emission in GaN:Si decreases relative to the free carrier concentration, the yellow-band intensity increases, and the donor-to-acceptor pair emission is not observed at all.

4:30 PM

Yellow Luminescence and Electrical Conductivity in GaN: *Ilan Shalish*[1]; Leeor Kronik[1]; Yoram Shapira[1]; Joseph Salzman[2]; [1]Tel-Aviv University, Dept. of Physical Electronics, Tel-Aviv 69978 Israel; [2]Technion-Israel Insititute of Technology, Elect. Eng., Solid-state Institute and Microelectronics Center, Haifa 32000 Israel

Despite numerous technological breakthroughs, even device grade GaN films still exhibit a high density of grain boundaries, as well as various extended and point defects. This typically results in a large density of gap states. Several important phenomena in GaN films have been generally attributed to defects, but otherwise do not seem to share an immediate common denominator. These phenomena include the ubiquitous yellow luminescence (YL), a persistent and non-exponentially decaying photoconductivity, a large ultra-violet photo-response gain, an exponential dependence of the conductivity on the implanted ion dose, and a wide range of reported electron mobility values. Finally, the riddle of how lasing can exist in a material so densely populated with defects is yet unsolved. Understanding the activity of gap states and their relation to the above phenomena is therefore of much importance for assessing their impact on device performance. Here, we suggest a model which inclusively accounts for the above listed phenomena. Our model is based on detailed investigations of the well-known YL and its related phenomena in GaN. We have augmented the customary emission-sensing PL measurements with two complementary absorption-sensing deep level techniques - surface photovoltage spectroscopy (SPS) and photoconductivity. The combined results show that the YL-related transitions involve a broad gap state, centered at ~2.2 eV below the conduction band minimum (and not above the valence band maximum). Furthermore, this state is of an acceptor nature. An apparent contradiction between the SPS and photoconductivity data is that the former suggest a significant concentration of YL-related gap states at the surface, whereas the latter suggest that the states are distributed in the bulk of the film. This seeming contradiction is easily settled if one assumes that the YL-related gap states are situated at grain boundaries, of which the free surface is a special case. This provides a basis for explaining all other phenomena given above by means of a well-established model of grain boundary controlled transport. According to this model, each boundary poses a potential barrier, the height of which is the main light sensitive parameter affecting the transport. One prediction of this model is an exponential dependence of the conductivity on the barrier height. We confirm this prediction by measuring the dependence of the photoconductivity on the surface potential barrier height, which is related to the grain boundary potential barrier.

4:50 PM

Electric Force Microscopy of Induced Charges and Surface Potentials in GaN Modified by Light and Strain: *P. M. Bridger*[1]; Zvonimir Z. Bandic[1]; Eric C. Piquette[1]; T. C. McGill[1]; [1]California Institute of Technology, Applied Phys., Mail Stop 128-95, Pasadena, CA 91125 USA

We have studied molecular beam epitaxy (MBE) grown GaN films of both polarities using electric force microscopy to detect sub 1 micron regions of electric field gradient and surface potential variations associated with GaN extended defects. The large piezoelectric coefficients of GaN together with strain introduced by crystalline imperfections produce variation in piezoelectrically induced electric fields around these defects. The consequent spatial rearrangement of charges can be detected by electrostatic force microscopy, and can be additionally modified by externally applied strain and illumination. The EFM signal was found to be a function of the applied tip bias, showed reversal under externally applied strain, and was sensitive to above band gap illumination. The size of the observed features correspond to the characteristic Debye length of the semiconductor and are attributed to charge screening of both the permanent polarization and piezoelectrically enhanced surface charge.

Session GG. Epitaxy of II-VI and Chalcopyrites

Friday PM   Room: State Street
July 2, 1999   Location: University Center

Session Chair: Charles Tu, University of California-San Diego, La Jolla, CA USA

1:30 PM

Homoepitaxy of ZnTe by MBE: *J. H. Chang*[1]; H. M. Wang[1]; K. Arai[1]; M. W. Cho[1]; K. Godo[1]; H. Makino[1]; T. Hanada[1]; K. Satoh[2]; O. Oda[2]; T. Yao[1]; [1]Tohoku University, Institute for Mats. Research, 2-1-1 Katahira, Aoba-ku, Sendai, 980-8577 Japan; [2]Japan Energy Corporation, Central R&D Laboratory, Japan

ZnTe, which has a direct bandgap of 2.27 eV, is one of the most promising materials for pure-green light emitters, since the pure-green wavelength range (540~570 nm) lies in the extreme wavelength regimes for both GaN-(Blue-Green: InGaN) and AlGaInP-(Yellow) based light emitters. In view of the recent rapid progress of ZnSe-based blue-green LD's fabricated on ZnSe substrates[1], the growth of device quality ZnTe-based materials on conductive ZnTe substrates is prerequisite to fabricate reliable pure-green light emitters. In contrast to homoepitaxy, heterovalent epitaxial growth has disadvantages such as large lattice and thermal mismatches with the substrate, impurity out-diffusion from the substrate and defect generation from the heterovalent interfaces. This study will report the homoepitaxial growth of ZnTe films including substrate preparation, surface treatments of the substrate prior to growth, growth and characterization of epilayers. P-type ZnTe substrates [2] grown by the vertical Bridgman method were characterized by high resolution X-ray diffraction (HRXRD) and atomic force microscopy (AFM). Chemical etching was performed using Br-methanol solution to remove residual surface damages and contamination. The etched surface shows a smooth surface with a surface roughness root mean square (RMS) value of less than 1 nm. The XRD measurement revealed a narrow diffraction peak with a FWHM value < 20 arcsec, which suggests the removal of surface damages. It is found that oxide- and hydrocarbon-related contamination are removed by heating the substrate at around 350°C in UHV as investigated by in-line Auger electron spectroscopy. To avoid surface roughening during thermal treatment, the exposure of either group II or VI elemental beams during thermal cleaning has been investigated. The surface morphology is greatly improved by simultaneous exposure of Zn and Te beams which resulted in the (2x1) reconstructed surface indicative of a Te stabilized surface. ZnTe films were grown in a temperature range of 280~320°C using the 2- step growth, in which a thin buffer layer is predeposited at 230°C followed by higher temperature growth. The low-temperature buffer layer is introduced to reduce the effects of residual surface contamination thereby improve the crystal quality of the overlayers. We note that two-dimensional growth dominated from the very beginning of growth as indicated by RHEED. HRXRD measurements on homoepitaxy layers revealed good crystallinity with a narrow FWHM value of 24 arcsec. We note that this FWHM value is considerably narrower than those from heteroepitaxial layers, typical value of which is 200 arc sec. Further improvement would be possible by optimizing the chemical etching and surface treatments of ZnTe substrates, which is under being investigated. Low-temperature photoluminescence (PL) spectra from homoepitaxy layers are dominated by excitonic emission with very week defects- and oxygen-related emission, which again shows high quality of the homoepitaxy layers. Reflectance spectra of the ZnTe layers show clearly resolved features due to excitonic transition up to 110 K, which enables to estimate an exciton binding energy of 13 meV. In conclusion, we have succeeded in MBE growth of device quality homoepitaxial ZnTe layers for pure-green light-emitting devices in terms of HRXRD and PL measurements. Extensive studies on chemical

and thermal treatments of ZnTe surfaces have been performed to remove the damaged surface layers, to minimize the surface contamination, and to obtain a smooth surface, which are needed to grow high quality layers. The effects of the residual surface contamination have been minimized by adopting the two-step growth method, thereby a two-dimensional growth is achieved from the very beginning of growth. References [1] K. Katayama et al., Proceedings of Intl. Symp. on Blue LD and LED, 1996, 340[2] Y. Seki et al., J. of Cryst. Growth 171, 1997, 32.

1:50 PM
High Quality ZnSeLayers with an Atomically Flat Surface Grown on GaAs (001) by Molecular Beam Epitaxy: *Kenat Arai*[1]; Akihiro Ohtake[2]; Takashi Hanada[1]; Tetsuji Yasuda[3]; Takafumi Yao[1]; [1]Tohoku University, Institute for Mats. Research, 2-1-1, Katahira, Aoba, Sendai 980-8577 Japan; [2]Joint Research Center for Atom Technology, Angstrom Technology Partnership, 1-1-4, Higashi, Tsukuba 305-0046 Japan; [3]Joint Research Center for Atom Technology, National Institute for Advanced Interdisciplinary Research, 1-1-4, Higashi, Tsukuba 305-0046 Japan

Recent study on ZnSe-based blue-green laser diode's (LD's) has indicated that improvement of the ZnCdSe active layer lead to prolonged life time of the LD, since point defects are responsible for the long-term degradation [1]. If this is the case, a drastic improvement in crystallinity would realize much longer laser life time. This study reports molecular beam epitaxial (MBE) growth of high quality ZnSe layers with an atomically smooth surface by employing the two-step growth method, in which a few monolayer of low-temperature buffer layer is predeposited onto a GaAs (001) substrate followed by a high temperature growth of ZnSe layers. In order to improve crystal quality, the growth of epilayers under a step-flow growth mode would be preferable, since the diffusion length of adatoms are sufficiently long. Extensive investigation on the reflection high energy electron diffraction (RHEED) intensity behaviors during MBE growth of ZnSe has been performed at various substrate temperatures varying from 255 to 395°C under stoichiometric growth conditions as indicated by a mixture of c(2x2) and (2x1) reconstruction pattern. RHEED intensity oscillations are observed for substrate temperatures of 255 - 335°C, which evidences that ZnSe layers grow under a two-dimensional nucleation and growth mode. The RHEED intensity oscillation disappears at a substrate temperature of 355°C, which is indicative of a transition of the growth mode from two-dimensional nucleation and growth to a step flow growth mode. This is supported by the roughness measurements with the atomic force microscopy (AFM). The root-mean-square (rms) value of the surface roughness of ZnSe epilayers decreases with increasing the substrate temperature from 255 to 355°C with the rms value being 0.29 nm for ZnSe films grown at 255°C and 0.17 nm at 355°C. However, we found it impossible to grow ZnSe layers with smooth surface at much higher substrate temperatures due to the deterioration of interface properties. The Se reaction with GaAs surfaces is enhanced at high substrate temperatures, which results in the formation of GaSe-related interface layers. The formation of GaSe layer on the GaAs surface promotes three-dimensional growth. Hence we have employed the two-step growth method, in which a few-monolayer thick ZnSe layer is deposited at 255°C onto a Zn-exposed GaAs (001)-(2x4) surface followed by the high temperature growth of ZnSe at 395°C. The typical rms value of a ZnSe layer grown by the two-step method was as low as 0.14 nm. It is expected that CdSe quantum dots would be formed with better controllability of both size and distribution on such an atomically flat surface by the self-organized mode than those fabricated on ZnSe surfaces prepared under conventional growth conditions typical rms value of which was 0.5 nm [2]. In consistent with the surface roughness, the full width at half maximum (FWHM) value of ZnSe (004) X-ray rocking curve decreases with increasing the substrate temperature: the FWHM value of a ZnSe film grown at 255°C was 186 arcsec, while that at 355°C was 166 arcsec. Considerable improvement is achieved by employing the two-step growth mode: typical FWHM value of a ZnSe layer grown by the two-step growth is 116 arcsec, which is to knowledge the narrowest value for ZnSe grown on (001) GaAs substrates. Photoluminescence (PL) properties are found to be consistent with the characterization by AFM and XRD. Low-temperature PL spectra are dominated by excitonic emission lines, in which both free

exciton emission and bound exciton emission at neutral donors are observed. The intensity of free exciton emission increases with increasing the substrate temperature by orders of magnitude. Such a increase implies the reduction of nonradiative centers in ZnSe layers, which will improve the laser lifetime if the layer is used in the devices. [1] E. Kato et al., Electron Lett., 34, 282 (1998).[2] Y. Qui et al., J. Appl Phys. 79, 1164 (1996).

2:10 PM
Growth and Characterization of Multiple Quantum Wells of $ZnSn(P_xAs_{1-x})$/GaAs: *Georgiy A. Seryogin*[1]; Sergey A. Nikishin[1]; Henryk Temkin[1]; [1]Texas Tech University, Dept. of Elect. Eng., MS3102, Lubbock, TX 79407 USA

Bulk $ZnSnP_2$ is known to have crystalline modifications - ordered (chalcopyrite) and disordered (sphalerite), with band gaps of 1.24 eV and 1.66 eV, respectively. Bulk $ZnSnAs_2$ has a band gap of 0.75 eV. We have recently reported successful growth of both phases of $ZnSnP_2$ on GaAs, and the growth of $ZnSnAs_2$ on InP. We report here on the growth of high quality single phase layers and quantum wells of quaternary $ZnSn(P_xAs_{1-x})$ on GaAs by gas source molecular beam epitaxy. Epitaxial layers were grown using conventional solid sources of Zn, Sn and Ga, and thermally cracker arsine (AsH_3) and phosphine (PH_3) as a sources of As and P. The best results for $ZnSnP_2$ were obtained at a growth temperature of 350-360⁰C. In order to obtain sphalerite structure, the Sn/Zn flux ratio was maintained at approximately 0.12-0.14 with excess phosphorus flux. The chalcopyrite structure could be grown at the Sn/Zn flux ratio of 0.24-0.26. Quaternary layer composition was estimated using Vegard's law and previously measured lattice constants for epitaxially grown $ZnSnAs_2$ and $ZnSnP_2$. We were able to prepare high quality sphalerite structure layers with the As content up to 17%. Superlattices contained 10 quantum wells of $ZnSn(P_xAs_{1-x})$ with 20 nm thick GaAs spacing layers. Thickness of $ZnSn(P_xAs_{1-x})$ varies with samples from 9 nm to 20 nm. Period of each superlattice was calculated from high resolution X-ray diffraction patterns. Excellent agreement was obtained with direct measurements of the total layer thickness and estimates based on growth rates of GaAs and $ZnSnP_2$. Photoluminescence properties of studied quantum well structures were investigated as a function of temperature and incident intensity. Room-temperature photoluminescence was observed at 1.16 eV from a sample containing 17 nm wells. This is consistent with the quaternary nature of the well material. Growth conditions leading to the preparation of quaternary chalcopyrite wells will be discussed.

2:30 PM
Epitaxial Growth of ɡ-In_2Se_3 Films with a Defect Wurtzite Structure by Molecular Beam Epitaxy: *Tomohiko Ohtsuka*[1]; Tamotsu Okamoto[2]; Akira Yamada[1]; Makoto Konagai[1]; [1]Tokyo Institute of Technology, Dept. of Elect. and Electr. Eng., Faculty of Eng., 2-12-1, O-okayama, Meguro-ku, Tokyo 152-8552 Japan; [2]Tokyo Institute of Technology, Reserch Center for Quantum Effect Electronics, 2-12-1, O-okayama, Meguro-ku, Tokyo 152-8552 Japan

III_2-VI_3 compound semiconductors such as Ga_2Se_3 and In_2Se_3 have unique properties that originate in their crystal structure. In_2Se_3 has two crystal structures at room-temperature (RT), i.e., a layered structure (a-phase) and a defect wurtzite structure (ɡ-phase). The layered structure of a-In_2Se_3 consists of rather loose stacks of covalently bonded layers, including five atomic layers of Se-In-Se-In-Se. The layered structure is considered to be a spontaneous superlattice perpendicular to the layers, and unique properties such as electrical and optical anisotropies are observed. In contrast, the structure of ɡ-In_2Se_3 is basically a wurtzite structure, but vacancies take a screw arrangement in the [001] direction. Therefore, this structure shows large optical rotatory power. In_2Se_3 is hopeful candidate for future optoelectronic material for these properties. However, there were no reports on the epitaxial growth of In_2Se_3 films. To date, we have investigated the epitaxial growth of In_2Se_3 films by the molecular beam epitaxy (MBE) technique, and a-In_2Se_3 epitaxial films with the layered structure based on the zincblende structure were successfully grown on GaAs(001) substrates. In this paper, we report on the epitaxial growth of ɡ-In_2Se_3 films by using GaAs(111)B substrates. The growth temperature was varied in the range of 380°C to 540°C. In beam flux was fixed at 4x10⁻⁷Torr and VI/III beam flux ratio was varied in the range of 3 to 150 by controlling the Se beam flux. Growth time

was 1h and film thickness was approximately 1000nm. ɤ-In$_2$Se$_3$ epitaxial films were obtained on GaAs(111)B at the growth temperature in the range of 400°C to 480°C, and at the VI/III ratios in the range of 5 to 15. The X-ray diffraction (XRD) pattern revealed that the lattice constant was approximately 1.95nm, which was almost same as the reported lattice constant parallel to the c-axis of ɤ-In$_2$Se$_3$. From this result, c-axis-oriented ɤ-In$_2$Se$_3$ epitaxial film was found to be grown on GaAs(111)B. Next, we observed the surface morphology of the ɤ-In$_2$Se$_3$ epitaxial films by atomic force microscope (AFM). Fig.1 shows the surface morphology. Hexagonal cone structure was observed on the surface of the ɤ-In$_2$Se$_3$ epitaxial films. This reflects the defect wurtzite structure of the ɤ-In$_2$Se$_3$. Furthermore, we investigated the electrical and optical properties of the ɤ-In$_2$Se$_3$ epitaxial films by means of photoconductivity and photoluminescence (PL) measurements. The photoconductivity spectrum shows photo absorption in the wavelength range less than 700nm at RT. The dark conductivity was approximately 1×10^{-4}S/cm at RT. Fig.2 shows the PL spectrum at 4.2K. Very strong excitonic luminescence was observed at around 580nm, suggesting the good optical property of the epitaxial ɤ-In$_2$Se$_3$ films. The bandgap of ɤ-In$_2$Se$_3$ at RT is estimated approximately 1.9eV by the temperature dependence of the PL peak energy.

2:50 PM Late News

3:10 PM Break

Session HH. Epitaxy of Si, III-V, Oxides

Friday PM   Room: Santa Barbara Harbor
July 2, 1999   Location: University Center

Session Chair: Colombo Bolognesi, Simon Fraser University, Dept. of Elect. Eng., Burnaby, BC Canada

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Characterization of Silicon Atomic-Layer-Epitaxy by an Atomic-Force Microscope: *Keiji Ikeda*[1]; Yasuo Satoh[1]; Satoshi Sugahara[1]; Masakiyo Matsumura[1]; [1]Tokyo Institute of Technology, Dept. of Phys. Electr., 2-12-1, O-okayama, Meguro-ku, Tokyo 152-8550 Japan

Si atomic-layer-epitaxy (ALE) has been achieved on the Si(100) surface, for the first time, and it was characterized by using an atomic force microscope (AFM). The excess growth rate caused by dynamic and non-ideal chemical processes on the surface was estimated as small as 1% of the ideal value (1ML/cycle) when the growth conditions were in the ALE window. ALE on the Si(100) surface was achieved by cyclic exposure of atomic hydrogen and dichlorosilane for the temperature window between 525°C and 625°C. Although the temperature window did not differ so much from that for the Si(111) surface[1], the dosage window of atomic hydrogen was found to be very narrow for the Si(100) surface due to etching effects of atomic hydrogen. This may be caused by the fact that there are only two back bonds for a surface Si atom on the (100) plane but three bonds on the (111) plane. The root-mean-square surface roughness has been measured by an AFM. The excess roughness (R) after 100 ALE cycles was as small as 1.7A when the growth conditions were in the ALE window, but increased abruptly when the conditions were out of the dosage window of atomic hydrogen. And R in the ALE window enlarged steadily with the execution cycle number. Deviation (D) of the growth rate from the ideal value i.e., 1ML/cycle was estimated theoretically under the assumption that it is caused by random and non-ideal mechanisms. Results were compared with experimentally measured R values, leading to the conclusion that /010// was as small as 0.01ML/cycle at 550°C. With elevating the temperature, D increased steadily and became 0.04ML/cycle at 600 ° C. These features were well characterized by atomic hydrogen-induced

etching in an atomic hydrogen exposure phase and spontaneous thermal-desorption of surface terminating Cl, having a form of SiCl2, in the dichlorosilane exposure phase and its evacuation phase. Since they are of dynamic processes, smaller D value will be obtained by shortening these periods, which were fixed at 20s in this work. References.[1] E.Hasunuma et al.:J. Vac. Sci. Technol. A 16(2) (1998) 679.

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Surface Phases of InP (001) in the MOVPE Process: *Robert F. Hicks*[1]; Lian Li[1]; Byung-Kwon Han[1]; Daniel Law[1]; Qiang Fu[1]; Connie Li[1]; [1]University of California, Chem. Eng. Dept., Los Angeles, CA 90095

Indium phosphide on InP (001) was grown by metalorganic vapor-phase epitaxy (MOVPE) under a variety of conditions. Growth was interrupted and the crystal transferred directly to an ultrahigh vacuum and surface characterized by scanning tunneling microscopy, x-ray photoemission, and vibrational spectroscopy. Indium phosphide (001) exhibits two structures, the P-rich (2x1) and the In-rich (2x4). The (2x1) is formed at V/III ratios greater than 20 and consists of a complete layer of buckled phosphorous dimers. The dangling bonds on these dimers are reactive, and during growth become covered with hydrogen and tertiarybutyl radicals. Below a V/III ratio of 20, a (2x4) reconstruction is observed, which is terminated with a mixture of indium and phosphorus dimers. These dimers are less reactive than those on the (2x1), but do become covered with adsorbates during growth. The (2x1) and (2x4) phases are completely miscible in one another, and their distribution on the surface depends on the growth conditions. These results and their implications for the MOVPE process will be described at the meeting.

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The Structure of Aluminum Antimonide Surfaces Grown by Molecular Beam Epitaxy: *Allan S. Bracker*[1]; William Barvosa-Carter[1]; James C. Culbertson[1]; Brian R. Bennett[1]; Lloyd J. Whitman[1]; Benjamin V. Shanabrook[1]; [1]Naval Research Laboratory, Electronics Sci. and Tech. Div., Code 6876, 4555 Overlook Ave., SW, Washington, DC 20375 USA

The quality of interfaces in semiconductor heterostructures can have a critical effect on device performance. Minimizing roughness and intermixing at interfaces will reduce carrier scattering, thereby improving transport both parallel and perpendicular to the heterostructure interface. This in turn will permit operation of electronic and optoelectronic devices at higher speed and lower power dissipation. We are particularly interested in improving the performance of high speed logic devices which combine high-electron-mobility transistors (HEMTs) and resonant interband tunneling diodes (RITDs). In the 6.1A compound semiconductor system, AlSb is frequently used as a barrier material. We have undertaken a study of AlSb (001) surfaces grown by molecular beam epitaxy, using RHEED and STM to probe the atomic-scale structure and islanding dynamics of the surface. We have started by investigating the detailed AlSb surface structure, including stoichiometry and reconstruction, that are prepared under a variety of conditions. These surface properties are likely to influence growth of additional material. For example, antimony-rich surfaces may be an unintendend source of compositional grading, since subsequent heterostructure layers can incorporate the extra atoms. Surface stoichiometry may also play a role in subsequent island formation and interface roughness. It is well known that during AlSb growth the RHEED pattern has a (1x3) symmetry. Under a variety of conditions, we have also observed faint streaks suggesting (4x3) symmetry. The pattern becomes sharper and stronger under conditions of low antimony flux and high substrate temperature (>550°C), suggesting the change in symmetry is associated with a lower Sb:Al surface coverage ratio. Filled-state STM images of these surfaces indicate they have at least two distinct reconstructions, both dominated by (1x3)-like rows oriented along [-1 1 0] (the 1x direction) with periodic "defects" along each row. In one reconstruction the rows appear to consist of Sb dimers, but every fourth dimer looks very asymmetrical (as if one atom is missing). The other reconstruction usually has a scalloped appearance, and it looks as if the Sb dimer rows are replaced by strings of monomers interrupted by similar 4x defects. Most of the surfaces that we have examined contain a mixture of these two reconstructions.

Although at low er temperatures short range disorder prevents the 4x symmetry from appearing in the RHEED, the characteristic defects are still observed in the surface topography. We have also initiated an investigation of the growth process by preparing a series of partial-monolayer additions onto flat, ordered AlSb (4x3) surfaces. We find that island coverages are routinely 10-30% higher than we would expect from the calibrated addition of Group III and V species. For flat surfaces prepared above 550°C, even a brief antimony flux at lower temperature (430°C) leads to island formation. We also observe that the islands are elongated in the [110] direction and island growth is inhibited along the upper ledge of step edges. We discuss possible mechanisms for these growth observations, including a possible role for the underlying surface structure and stoichiometry.

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MBE Growth of ZnO Films on GaN and Characterization: *H. J. Ko*[1]; Y. F. Chen[1]; S. K. Hong[1]; T. Yao[1]; [1]Tohoku University, Institute for Mats. Research, 2-1-1 Katahira, Aoba-ku, Sendai 980 Japan

ZnO has a direct bandgap of 3.37 eV with an extremely large excitonic binding energy of 60 meV. Very recent achievements on high temperature excitonic stimulated emission and excitonic lasing from ZnO films [1,2] have proven that ZnO is promising for exploring excitonic devices in the uv wavelength range. The ZnO films were grown on Al_2O_3 substrates [3,4], where the lattice mismatch is as large as 18 %. Although ZnO films grown on Al_2O_3 have shown the promising optical properties, the crystal quality of the layers is still needed to be improved due the presence of high density defects at around the interface[3,4]. The use of smaller lattice-mismatched substrates would improve the ZnO film quality. This paper presents the first report on plasma-assisted MBE growth of ZnO on closely lattice-matched epi-GaN/ Al_2O_3, where the lattice mismatch is reduced to 1.8 %. It is found that the surface preparation of the GaN surface has crucial role in both the growth mode and crystal quality of ZnO overlayers. Two types of pregrowth treatments on a GaN surface either by Zn- or oxygen-plasma-exposure have been investigated, where GaN layers were grown on Al2O3 by MOCVD. The surface of MOCVD-grown GaN layers were found to be terminated by Ga atoms as determined by ion-beam analysis. After the pregrowth treatment, a thin ZnO buffer layer is deposited followed by annealing and successive ZnO growth at higher temperatures. We observed RHEED intensity oscillations from the very beginning of ZnO growth on the low temperature ZnO buffer layer predeposited on Zn-exposed GaN surfaces. This is a clear indication of two-dimensional nucleation and growth mode. Furthermore, clear transition from the two-dimensional nucleation and growth mode to step-flow growth one is observed by changing the growth conditions in terms of RHEED observation. In accord with the two-dimensional growth mode, ZnO films grown on Zn-exposed epi-GaN show the same FWHM value of X-ray diffraction rocking curve as that of eip-GaN substrates which is typically 5arcmin, suggesting that the film quality is limited by the quality of the substrate. We note that the line shape of the diffraction curve of ZnO films is Gaussian, although the line shape occasionally consists of the main peak and a long tail in the diffraction curve of ZnO and GaN layers grown on Al_2O_3. In contrast to ZnO films grown on Zn exposed epi-GaN substrates, those grown on oxygen plasma exposed epi-GaN showed broader XRD curve with twice FWHM values of eip-GaN. The difference in the crystal quality of ZnO layers grown on Zn- and O-exposed epi-GaN would be ascribed to the different interface structures produced by the two exposures as observed by TEM. The ZnO/GaN interface for the Zn exposure shows a clear interface without an interface layer, while O-exposed interface shows an interface layer of ca 5 ML thick. The O-exposed interface is tentatively assumed to be a GaO-related compound as is the case for ZnSe layers grown on Se-exposed GaAs which produces a GaSe-related interface layers. As similar to the case for ZnSe/GaAs, both types and numbers of defects differ by changing the pregrowth treatments. Low temperature (4 K) photoluminescence spectrum from ZnO layers grow on Zn-exposed epi-GaN is dominated by two distinct excitonic emissions with a hump due to free-exciton emission. The line widths of the two emission lines are 4 meV. Deep level emission is negligible and cannot be detected up to room-temperature. Reference 1 D.M. Bagnall, Y.F.Chen, Z.Zhu, T.Yao, S.Koyama, M.Y.Shen, T.Goto, Appl.Phys.Lett. 70, 2230(1997) 2 D.M.Bagnall, Y.F.Chen, Z.Zhu, T.Yao, M.Y.Shen, T.Goto, Nonlinear Optics 18(2-4), 243(1997) 3 Z.K.Tang, G.K.L.Wong, P.Yu, M.Kawasaki, A.Ohtomo,H.Koinuma, Y.Segawa Appl. Phys. Lett. 72, 3270(1988) 4 Y.F.Chen, D.M.Bagnall, H.J.Ko, K.T.Park, K.J.Hiraga, Z.Zhu, T.Yao Appl. Phys. Lett. 84, 3912(1998)

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Plasma Assisted Molecular Beam Epitaxy and Characterization of the MgxZn1-xO/ZnO Hetero-Structures: *Yefan Chen*[1]; Takafumi Yao[1]; Yosaburo Segawa[2]; Hang-ju Ko[1]; Soon-ku Hong[1]; [1]Tohoku University, Institute for Mats. Research, Katahira 2-1-1, Aoba-ku, Sendai, Miyagi-ken 980-0821 Japan; [2]The Institute of Physical and Chemical Research, Photon Dynamics Research Center, Koeji 19-1399, Nagamachi Aoba-ku, Sendai, Miyagi-ken Japan

The desire to produce short wavelength semiconductor lasers has motivated research into low dimensional structures of wide band-gap materials such as those based on ZnSe and GaN systems. The excitonic nature of these materials have proved to be of particular interest because of the lower threshold for excitonic laser action compared with the lasing due to conventional electron hole plasma. However, for this effect to be of practical value the exciton must survive at elevated temperatures. Unfortunately, without significant enhancement of binding energies by quantum confinement the excitons of ZnSe and GaN can not be efficiently utilized at room-temperature. One of the most promising long-term alternatives to the GaN and ZnSe based systems in this regard is ZnO. It has a room-temperature band-gap of 3.37 eV and the exciton binding energy of 60 meV, which ensures excitonic survival well above room-temperature. Recently, innovative growth technique[1] has allowed observations of high temperature stimulated emission[2] and optically pumped lasing from ZnO at room-temperature[3], where exciton-exciton scattering is responsible for the stimulated emission and lasing. To achieve the ZnO based quantum structural devices (here, the excitonic nature plays even more important role because of the enhancement of exciton oscillator strength as well as its binding energy), MgxZn1-xO alloys is chosen for the barrier material. Although ZnO and MgO have different crystal structures of the wurtzite and rocksalt type respectively, the wurtzite structural MgxZn1-xO alloy (powder) can exists until x exceeds 30%, meanwhile, the change of in-plane lattice constant a is less than 1%. Since MgO has band-gap larger than 7 eV, the band-gap tuning by incorporating Mg into ZnO will also be significant. However, so far, both the thin film growth techniques and intrinsic properties of the single crystal remain to been explored. Here, we report on the plasma assisted molecular beam epitaxy of the MgxZn1-xO/ZnO hetero-structures, as well as their structural and optical characterization. By using 2-axis scan of high resolution X-ray diffraction the lattice constants of both a and c are directly determined for the alloys. Band-gap energy is investigated by absorption and reflectance spectroscopy. ZnO/MgxZn1-xO single quantum wells with different well widths are grown and investigated by cathodeluminescence. Emissions from recombination of localized excitons are observed and the well width effects are studied. 1. Yefan Chen, D. M. Bagnall, Hang-ju Koh, Ki-tae Park, Kenji Hiraga, Ziqiang Zhu, and Takafumi Yao, J. Appl. Phys. Vol. 84, 3912 (1998). 2. D. M. Bagnall, Y. F. Chen, Z. Zhu, T. Yao, S. Koyama, M. Y. Shen, and T. Goto, Appl. Phys. Lett. Vol. 70, 2230 (1997). 3. D. M. Bagnall, Y. F. Chen, Z. Zhu, T. Yao, M. Y. Shen, T. Goto, Appl. Phys. Lett. Vol. 73, 1038 (1998).

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