

EMC Plenary Lecture/Student Awards

Wednesday AM
June 20, 2007

Room: Leighton Concert Hall
Location: DeBartolo Performing Arts Center

8:20 AM Awards Ceremony

8:30 AM Plenary

Low Cost "Plastic" Solar Cells: A Dream or Reality???: Alan Heeger¹;
¹University of California, Santa Barbara

Polymer solar cells with power conversion efficiencies in excess of 5% are demonstrated using bulk heterojunction materials. Spatial Fourier transform methods have been used to study and optimize the morphology. Light harvesting has been improved by using a novel low-bandgap conjugated polymer, with an optical energy gap of $E_g \sim 1.5$ eV. Solar cells with a TiO_x layer (deposited by a sol-gel process) between the active layer and the electron collecting aluminum electrode exhibit enhanced power conversion efficiency and significantly improved lifetime compared to similar devices without the TiO_x layer. The use of TiO_x provides several important opportunities; specifically, the TiO_x layers enable higher performance from single cells, longer lifetime as a result of reduced sensitivity of the solar cell to oxygen and water vapor, and the fabrication of bulk heterojunction cells in the 'Tandem Cell' architecture, a multilayer structure that is equivalent to two photovoltaic cells in series.

9:20 AM Break

Session A: Chemical and Biological Sensors I

Wednesday AM
June 20, 2007

Room: 126
Location: DeBartolo Hall

Session Chairs: Alec Talin, Sandia National Laboratories; Ray Tsui, Motorola Laboratories

10:00 AM

A1, Gateless GaN/AlGa_N BioFETs for Direct Biomolecular Detection: Kendra McCoy¹; Lloyd Whitman¹; ¹Naval Research Laboratory

BioFETs, Biologically modified field effect transistors (BioFETs) have the potential to directly detect biochemical interactions in aqueous solutions for a wide variety of sensing applications. In order for these devices to be useful, they must satisfy three major criteria. BioFETs must be stable in aqueous solutions across a range of pH and salt concentrations; the surfaces of these devices must be sensitive to biochemical interactions; and the devices must be able to probe specific biochemical interactions. BioFETs that we are developing and testing based on AlGa_N/GaN quantum well devices (provided by Nitronex Corporation) so far seem to satisfy all of these requirements. It has already been demonstrated that these AlGa_N/GaN quantum well devices can sense small changes in pH of electrolyte solutions. We have developed a simple, silane-free method to directly functionalize the device surfaces with a robust Neutravidin monolayer. Using this recognition layer, we have determined the conditions required to sense molecular recognition of biotin via changes in conductance. We have also used simple two-terminal devices to observe the real-time immobilization of biotinylated, single-stranded DNA. Characterization of the immobilized films by a variety of methods will be discussed, along with our progress towards real-time hybridization assays and immunoassays.

10:20 AM Student

A2, Surface Functionalization of AlGa_N for Biosensor Applications: Xuejin Wen¹; Mark Elias²; John Shapiro²; Lee Mosbacker¹; Samit Gupta²; Stephen Lee²; Leonard Brillson¹; Wu Lu¹; ¹Ohio State University, Department of Electrical and Computer Engineering; ²Ohio State University, Department of Biomedical Engineering

Label free biosensors based on electrical field effect transistors (FETs) are of great research interests. Si-based such biologically FETs (bioFETs) suffer from various difficulties such as limited sensitivity and current drift caused by degradation of gate dielectrics and chemical instability. Due to the chemical inertness and the high concentration of two dimensional electron gas (2DEG) at the AlGa_N/GaN interface, AlGa_N/GaN heterojunction FETs have great potentials for detection of bioagents. In this paper, we present the process and characterization of functionalization of AlGa_N surface for biosensing applications. The AlGa_N surface is naturally hydrophobic with a water contact angle of about 60°. The first step is to oxidize the AlGa_N surface to make it hydrophilic. Wet chemical, direct and remote plasma treatments are used to oxidize AlGa_N surfaces. The surface treated by wet chemicals has higher hydrophilicity (water contact angle <10°) than plasma treated surfaces (water contact angle about 25°). The O1s peaks of X-ray photoemission spectroscopy (XPS) show that direct plasma treatment is the most effective while remote plasma is the least. Secondly, 3-Aminopropyltriethoxysilane (APTES) is applied to the oxidized surface to deploy a self assembly monolayer (SAM) using the silane chemistry. N1s XPS spectra show peaks for amino tail groups at around 397 eV and 400 eV. As readily set up on silicon surfaces on Si-based BioFETs, the surface is biotinylated. A superblock layer is deposited to prevent non-specific binding of target protein. Labeled streptavidin is applied to check the binding specificity and the surface coverage. The samples treated by wet chemicals and direct plasma show similar fluorescence intensity, while the intensity on the remote plasma treated surface is weaker. To confirm the effectiveness of SAM layer depositions, samples treated under the same conditions except the biotin layer show essentially no fluorescence, indicating that there is no non-specific bonding between streptavidin and the surface. C-V measurements of Schottky diodes on oxidized AlGa_N/GaN heterostructures will be performed to characterize the effects of oxidation methods on the 2DEG concentration and the surface/interface defects induced during oxidation.

10:40 AM Student

A3, Thermodynamic Analysis of Hydrogen Sensing in Pt/AlGa_N/GaN Schottky Diodes: Jinghui Song¹; Wu Lu¹; ¹Ohio State University

GaN-based Schottky diodes have been demonstrated for hydrogen sensing in harsh environments.^{1,2} This paper presents the detailed thermodynamic analysis of Pt/AlGa_N/GaN heterojunction Schottky diodes for sensing of hydrogen gas. The devices have a circular sensing area with a diameter of 200 μm where the thin Pt catalytic film is coated. The steady state and transient characteristics are studied at different temperatures and hydrogen concentrations. At steady state conditions, both forward and reverse currents increase when the devices are exposed to hydrogen and the Schottky barrier height is lowered due to dissociation of hydrogen and the formation of a dipole layer at Pt/AlGa_N interface. At 300°C, the reverse and forward current increases from -0.8 μA in N_2 to -1 μA in 50 ppm hydrogen and from 2.75 mA to 3.46 mA at a bias of 1 V, respectively. The devices exhibit higher sensitivities at reverse biases, though the absolute current changes are much larger at forward biases. The sensitivity of devices also increases as the testing temperature or hydrogen concentration increases, e.g. from 0.23 at 25°C to 0.39 at 300°C and 50 ppm at a reverse bias of 1 V, due to more effective catalytic dissociation of H_2 . Based on the Langmuir isotherm adsorption process, at 50 ppm, the dissociated hydrogen coverage at Pt/AlGa_N interface is about 39% and 24% at 300°C and 25°C, respectively. The current at saturation adsorption (5.3 mA at 300°C) and the difference of hydrogen adsorption rate constants between the surface and interface (3.4 Torr^{-1/2}) are extracted from the current and hydrogen partial pressure dependence. The heat of adsorption is -21.6 kJ/mole, indicating that the reaction between H_2 in Pt/AlGa_N is exothermic. Transient measurements show that the sensor response time at different test conditions is in a range of few seconds. With higher H_2 concentration and at higher temperatures, the response time is shorter. The activation energy is extracted from transient characteristics at different temperatures and different H_2 concentrations. The results show that

the activation energy is larger at higher H_2 concentrations, with values of 0.62kJ/mole, 1.2kJ/mole, 1.58kJ/mole, and 5.11kJ/mole in 50, 200, 1000, and 5000 ppm H_2/N_2 , respectively. ¹J. Song, J. S. Flynn, G. R. Brandes, and W. Lu, *Appl. Phys. Lett.*, vol. 87, 133501 (2005). ²J. Song, W. Lu, J. S. Flynn, and G. R. Brandes, *Solid State Electronics*, vol. 49, 1330 (2005).

11:00 AM

A4, Performance Enhancement and Sensing Mechanism of Pd/AlGaIn/GaN Hydrogen Sensors Subjected to Oxygen Gettering: *Hideki Hasegawa*¹; Masamichi Akazawa¹; ¹Hokkaido University

Due to superb chemical stability of surface, environment-friendly nature and capability of high-temperature operation, the AlGaIn/GaN heterostructure is promising for chemical and bio-chemical sensor applications. It is an attractive platform for integrated wireless sensor chips where nano-scale sensors are co-integrated with AlGaIn/GaN HFET circuits for sensor signal processing and wireless communication. For such purposes, sensors should be directly formed on the AlGaIn/GaN heterostructure. However, large leakage currents in AlGaIn/GaN Schottky diodes and HFETs deteriorate sensor performances, as our initial work indicated.¹ This paper reports on performance enhancement and sensing mechanism of Pd/AlGaIn/GaN Schottky diode hydrogen sensors subjected to an oxygen gettering process. Planar circular Pd Schottky diodes with ring-shaped Ti/Al/Ti/Au ohmic electrodes were formed on AlGaIn (Al composition 0.25)/GaN HFET wafers. The oxygen gettering process² consisted of (1) covering the AlGaIn surface with an ultrathin Al film, (2) annealing in ultrahigh vacuum and (3) removing the Al film. This process reduced reverse leakage current by 5 orders of magnitude for Pd diodes. In-situ XPS analysis and Schottky C-V analysis supported gettering of oxygen from the AlGaIn surface region. The mechanism of leakage current and its reduction was explained by the thin surface barrier (TSB) model³ where oxygen shallow donors reduce the width of the Schottky barrier and cause thermionic field emission (TFE) transport. After oxygen gettering, I-V curves of the diode exhibited unprecedented high hydrogen sensitivity in air where orders of magnitude changes of currents took place, showing a systematic dependence on hydrogen partial pressure. In vacuum, the current change was even larger, but its dependence on hydrogen pressure was much weaker. The diodes showed fast turn-on and -off characteristics in air, although they showed very slow turn-off in vacuum. From detailed measurements of I-V, C-V and current transient characteristics, the sensing mechanism was explained in terms of Schottky barrier height (SBH) reduction caused by formation of interface dipole by atomic hydrogen (H^*) produced by Pd. Dipole formation is rate-limited by surface reaction rather than by interface adsorption. This leads to the Langmuir isotherm type coverage behaviour at interface. In air, reaction between H^* and oxygen at surface modifies supply and removal rates of H^* , whereas removal is very slow in vacuum. SBH values deduced from current changes were 1.6 times smaller than those by C-V analysis, and this discrepancy was quantitatively explained by the TFE process through the TSB region where current becomes less sensitive to SBH change due to tunnelling. ¹K. Matsuo, T. Hashizume and H. Hasegawa: *Appl. Surf. Sci.* 244 (2005) 273. ²J. Kotani, M. Kaneko, H. Hasegawa and T. Hashizume, *J. Vac. Sci. Technol. B* 24 (2006) 2148. ³H. Hasegawa and S. Oyama, *J. Vac. Sci. Technol. B* 20 (2002) 1647.

11:20 AM Student

A5, Effect of Alkaline Treatment on the Characteristics of AlInN/GaN Heterostructures in Electrolytes: *Carsten Pietzka*¹; Andrej Denisenko¹; Farid Medjdoub¹; Erhard Kohn¹; Jean-Francois Carlin²; Eric Feltrin²; Nicolas Grandjean²; ¹University of Ulm; ²Ecole Polytechnique Fédérale de Lausanne

In this investigation we have evaluated the limit of the chemical stability and degradation mechanisms of InAlN/GaN HEMT-like heterostructures by treatment in strong basic solutions and under strong anodic polarization. InAlN/GaN heterostructures are considered extraordinarily stable as seen from the extraordinary temperature stability and corrosion resistance of HEMT device structures. The AlInN/GaN heterostructures were grown lattice matched on sapphire substrates by MOCVD. The AlInN barrier layer thickness was 10 nm, the 2DEG density $2.6E+13/cm^2$ and the carrier mobility $950 cm^2/Vsec$. The ChemFET structures were subjected to a successive anodic treatment in 0.1M KOH solution at room temperature. Their characteristics were analyzed in electrolytes with pH=1 and pH=13 both in the FET and in

the electrode modes. It was found that the pH-sensing characteristics of the ChemFETs were strongly affected by the alkaline treatment. The as-fabricated structure (Al-surface) did not show any pH sensitivity and transistor action. This indicated that the density of the chemically-active bonds on the AlInN surface was very low. The ChemFET characteristics and the pH sensitivity were observed after the first anodic treatment. Thus, new chemically active groups have been generated on the AlInN surface by the anodic oxidation. The oxidation-induced surface states pin the surface Fermi level, resulting in a partial depletion of the 2DEG channel in air. Additional subsequent anodic treatments in KOH increased the depletion of the 2DEG channel. However, no etching of the AlInN barrier layer was detected. Data on surface potential and the interfacial energy band-diagram in contact with the electrolyte will be given.

11:40 AM Student

A6, ZnO Film/ZnO Nanowire Arrays/ZnO Film Hybrid Nanostructures for Sensor Applications: *Min-Chang Jeong*¹; Byeong-Yun Oh¹; Sang-Won Lee¹; Jae-Min Myoung¹; ¹Yonsei University

One-dimensional (1-D) nanostructures have attracted great attention due to their extraordinary characteristics, such as high crystalline quality, large surface energy, high aspect ratio, and quantum effects. Among various 1-D nanostructures, ZnO nanowires have been intensively studied because of the reliable fabrication with the wide application fields. However, the fabrication and manipulation of ZnO nanowires for device applications still seem to be difficult and most of the device structures suggested to date have been based on single nanowire demonstrating development potentials. In this research, carefully designed ZnO hybrid nanostructures, composed of a bottom ZnO film, ZnO nanowire arrays, and a top ZnO film, were continuously fabricated by adjusting the supersaturation condition using metal-organic chemical vapor deposition (MOCVD) to utilize vertically aligned ZnO nanowires for the ultraviolet (UV) and oxygen sensing applications. Photocurrent was generated in ZnO nanowires only when the UV light was irradiated. The oxygen sensing characteristics of the hybrid nanostructures also confirmed and higher oxygen sensitivity was observed from the hybrid nanostructures having thinner diameters of nanowires. These sensing characteristics of the hybrid nanostructures are attributed to the photogenerated carriers and the surface reaction of negatively charged oxygen species on ZnO nanowires. By forming seamless interfacial contacts with a bottom film and a top film, superior photonic and electronic properties of ZnO nanowires could be directly exploited without complicated manipulation processing.

Session B: Organic/Inorganic Hybrid Photovoltaic

Wednesday AM
June 20, 2007

Room: 129
Location: DeBartolo Hall

Session Chairs: William Wong, Palo Alto Research Center; Max Shtein, University of Michigan

10:00 AM Student

B1, Surface Plasmon Polariton Mediated Energy Transfer in Organic Photovoltaic Devices: *Timothy Heidel*¹; Jon Mapel¹; Kemal Celebi¹; Madhusudan Singh¹; Marc Baldo¹; ¹Massachusetts Institute of Technology

Organic photovoltaics (PV) are constrained by a tradeoff between exciton diffusion and optical absorption. The short exciton diffusion length within organic semiconductors demands the use of extremely absorptive materials. Unfortunately, the excitonic character of most organic materials yields highly structured absorption spectra, with regions of strong and weak absorption. In this talk we propose a novel device architecture that decouples light absorption and exciton diffusion in organic PV through the addition of a light absorbing 'antenna' layer external to the conventional charge generating layers. Radiation absorbed by the antenna is transferred into the thin charge generating layers via surface plasmon polaritons (SPP) in an interfacial thin silver contact and radiation into waveguide modes. SPPs are a particularly effective energy transfer mechanism as they propagate in the plane of the

PV rather than parallel to the incident radiation, thereby providing a more efficient means of pumping thin charge generating structures. We first employ superlattice photodetectors with unity internal quantum efficiency to measure the efficiency of energy transfer across a thin silver film. We measure the efficiency of energy transfer to be at least (51±10)%. Next, we exploit efficient SPP-mediated energy transfer by attaching a resonant cavity antenna to a conventional small-molecular weight organic PV. We find that the resonant cavity antenna boosts the performance of a phthalocyanine-based PV in the absorption gap between the phthalocyanine Q and Soret bands. Off resonance the antenna serves as a mirror, but near the resonant wavelength, the antenna absorption is significantly enhanced, and energy is fed back into the PV cell via SPP-mediated energy transfer. Thus, the resonant antenna may be employed to supplement the performance of the PV cell at resonance, with no degradation off-resonance. Targeting resonant antennas to regions of poor absorption promises to solve a characteristic deficiency of organic PVs. Finally we discuss our results in the context of other architectures aimed at increasing light absorption in organic PV cells. Antennas compete principally with multiple-junction tandem PV cells, which have proved especially successful for inorganic semiconductors with band-to-band transitions. The structured absorption spectra characteristic of organic semiconductors, however, makes the design of multiple cells with orthogonal optical absorption and matched photocurrents difficult. While the introduction of an external light absorbing antenna necessarily adds a step into the energy transduction process, it can be successfully employed in spectral regions where the absorption fraction of the PV cell drops below the SPP-mediated energy transfer efficiency, i.e. $\eta_{\text{ABS}} < 50\%$. In addition, the antenna decouples photon absorption and exciton dissociation, allowing both properties to be separately optimized. Since the optically absorbent element need not conduct excitons or charge, new antenna materials are possible, including J-aggregates and quantum dots.

10:20 AM

B2, Fiber Based Organic Light Emitting Diodes and Photovoltaic Cells: *Brendan O'Connor*¹; Kwang Ann¹; Yiyang Zhao¹; Kevin Pipe¹; Max Shtein¹; ¹University of Michigan

In recent years, electronically functional fibers have gained increasing attention with their potential for aesthetic and ergonomic assimilation of our growing electronic device dependence into ever-present fabrics. In addition, optoelectronic fibers have potential for remote power generation with photovoltaic-based fibers, and large area lighting with electro-luminescent fibers both being integrated into large canvas materials. Organic materials are of particular interest for this realization, both as substrates and active layers, owing to their mechanical flexibility and potential for low cost manufacturability. Here, we demonstrate flexible fiber-based organic photovoltaic (OPV) cells. These devices consist of metallic anode and cathode, sandwiching layered molecular organic semiconductor compounds (e.g. CuPc, C60), all deposited sequentially and conformally onto polyimide coated silica fibers. Device growth is accomplished using vacuum thermal evaporation with the fiber axially rotating above the sublimated source material. We characterize the optoelectronic performance of these devices, analyze the physical effects that arise due to the non-planar geometry and present new fabrication and optimization methods for this device geometry. For example, the circular symmetry of the fiber is conducive to angularly uniform and enhanced light coupling into the device and controlled optical scattering in woven fiber assemblies. The fiber OPV cells exhibit power conversion efficiency comparable to planar cells of similar structure, and simulations indicate that bundled fibers with external coatings can further improve overall power conversion efficiency without relying on the commonly used indium-tin-oxide (ITO) electrode. Removing ITO allows for increased device flexibility and opens opportunities for high throughput roll-to-roll manufacturing. These results suggest that fiber based devices can potentially increase energy conversion efficiency, while broadening the range of fabrication approaches, thus providing a viable and convenient platform for integration of devices into woven fabrics and fabric-reinforced composites.

10:40 AM Student

B3, Subwavelength Metal Gratings as Flexible and Transparent Electrodes in Organic Thin-Film Photovoltaic Cells: *Jung-Yong Lee*¹; Peter Peumans¹; ¹Stanford University

Organic optoelectronic devices frequently make use of transparent, thin-film electrodes to provide electrical contact to the devices while not impeding coupling of light into and out of the devices. Usually, transparent and conductive metal oxides such as indium tin oxide (ITO) and fluorine-doped tin oxide (FTO) are used for this purpose. However, such materials have a number of disadvantages. The cost of sputtered thin films may be too high for low-cost applications such as organic solar cells and organic light-emitting diodes for lighting.¹ Moreover, the cost of ITO is likely to increase further due to the potential shortage of indium.² The brittle thin-film metal oxide electrodes on flexible substrates are known to crack when bent, leading to device failure.³ Furthermore, in cases where a transparent electrode is required on top of an organic layer, the sputter deposition of ITO onto an organic material is known to cause damage that leads to decrease in device performance.^{4,5} Lastly, materials such as ITO have poor transmittance in the infrared, reducing the light to electrical power conversion efficiency for that portion of the solar spectrum in photovoltaic cells. Several alternatives to sputtered thin-film metal oxides have been demonstrated.⁶ Recently, encouraging results were obtained with random networks of single wall carbon nanotubes when used as flexible contacts for organic photovoltaic cells.^{7,8} Here, we investigate the potential of one- and two-dimensional subwavelength metal gratings as flexible and transparent electrodes to organic solar cells. Using finite-element electromagnetic modeling in the optical domain, we show that the performance of these structures is similar to or better than that of ITO. Transmittance and photocurrent data on organic photovoltaic cells with metal grating electrodes will be presented and compared with conventional organic solar cells with ITO electrodes.

¹S. Forrest, Nature 428, 911-918 (2004). ²U.S. Department of the Interior, Mineral Commodity Summaries 2006. ³Z. Chen, B. Cotterell, W. Wang, E. Guenther, S. Chua, Thin Solid Films 394 202 2001. ⁴G. Gu, V. Bulovic, P. E. Burrows, S. R. Forrest, and M. E. Thompson, Appl. Phys. Lett. 68, 2606 1996. ⁵H. Kim, D. Kim, K. Lee, M. Huh, S. Jeong, K. Kim, T. Seong, Appl. Phys. Lett. 86, 183503 2005. ⁶H. Kim, A. Pique, Ki Horwitz, H. Murata, Z. Kafafi, C. Gilmore, D. Chrisey, Thin Solid Films, 377 798 2000. ⁷Z. Wu, Z. Chen, X. Du, J. M. Logan, J. Sippel, M. Nikolou, K. Kamaras, J. R. Reynolds, D. B. Tanner, A. F. Hebard, A. G. Rinzler, Science 305, 1273 (2004). ⁸M. Zhang, S. Fang, A. A. Zakhidov, S. B. Lee, A. E. Aliev, C. D. Williams, K. R. Atkinson, and R. H. Baughman. Science 309, 1215 (2005).

11:00 AM

B4, Flexible Conjugated Polymer Photovoltaic Cells with Controlled Nanoscale Heterojunctions Fabricated Using Nanoimprint Lithography: *Myung-Su Kim*¹; Jin-Sung Kim¹; Jaecheol Cho¹; Max Shtein¹; L. Guo¹; Jinsang Kim¹; ¹University of Michigan

Conjugated polymer (CP) solar cells offer an attractive alternative to silicon-based photovoltaic (PV) technology for low-cost solar energy conversion due to easy processability, compatibility with flexible substrates, and the tunable optoelectronic properties of the CPs. However, the power conversion efficiency remains low due in part to the inefficient exciton diffusion that typically precedes exciton dissociation in organic PV cells. Bulk heterojunction (BHJ) cells have been developed to improve exciton diffusion and dissociation, by creating phase-separated donor-acceptor domains. However, the resulting disordered morphology of BHJ severely limits separation and transport of the geminate charges to the electrodes. Here we demonstrate CP-based flexible solar cells with well-defined interdigitated donor-acceptor interfaces that enhance charge separation and transport. These devices are achieved using solution coating and nanoimprinting of the active polymer layers. Nanoimprinting enables the precise and direct nanoscale control of the shape of the donor-acceptor interface on both rigid and flexible substrates.

11:20 AM

B5, Electric-Field-Assisted Aerosol Deposition of Metal Nanoparticles for Surface-Plasmon-Enhanced Organic Photovoltaic Cells: *Shigeo Fujimori*¹; Rostam Dinyari¹; Jung-Yong Lee¹; Peter Peumans¹; ¹Stanford University

Metal nanostructures can confine and guide electromagnetic energy on a nanometer scale over a wide spectral range that covers the solar spectrum. Using finite-element modeling, we have shown that metal nanoparticles can be embedded into the active layers of organic photovoltaic cells to bring about large gains in efficiency and to tune the spectral response of the cell. Prior demonstrations based on bare metal nanoparticles required that the metal be spatially separated from the device active region to prevent exciton quenching by charge-transfer from the organic to the metal. Here, we use metal-core/insulator-shell nanoparticles at the donor-acceptor interface to maximize the increase in efficiency. Vacuum deposition cannot be used to fabricate such these hybrid devices with metal nanoparticles embedded at the donor-acceptor interface because the metal-core/insulator-shell nanoparticles are too heavy to sublime. Solution processing is not an option since it leads to undesirable morphologies. To address this challenge, we have developed an aerosol deposition technique to introduce metal-core/insulator-shell nanoparticles into organic thin-film devices in a vapor-phase process. In our method, droplets of an organic solvent containing the nanoparticles are transported in an inert carrier gas to a substrate after removal of the solvent by evaporation. To transport the nanoparticles to the substrate effectively, the droplets are charged by corona discharge and an electric field is used to assist delivery of the nanoparticles to the substrate. Surfactant-coated Au-nanoparticles were used to prevent the aggregation and were dispersed on the substrates by this electric-field-assisted aerosol deposition. We will discuss how the aerosol deposition method was optimized to achieve deposition without aggregation of the metal nanoparticles. Solar cell device results on organic donor-acceptor solar cells with surfactant-coated Au-nanoparticles embedded at the donor-acceptor interface will also be presented.

11:40 AM Student

B6, Matrix-Assisted Pulsed Laser Evaporation of Hybrid Colloidal Quantum Dot/Conducting Polymer Nanocomposite Heterostructures: *Ryan Pate*¹; Kevin Lantz¹; Adrienne Stiff-Roberts¹; ¹Duke University

Organic/inorganic semiconductor hybridization is a growing area of study due to the benefits of combining the optical and electrical properties of inorganic semiconductor quantum dots with the mechanical properties and manufacturing ease of polymers. Colloidal quantum dot (CQD)/conducting polymer nanocomposites have been shown to significantly improve the performance of solar cells when compared to their organic counterparts.¹ Such nanocomposites are also being investigated for LEDs, infrared photodetectors, and photorefractive waveguides. The typical methods for depositing these hybrid structures include drop-casting and spin-casting. However, inadequate control of film thickness and uniformity, as well as the inhomogeneous distribution of CQDs inside the polymer matrix, makes deposition consistency challenging. Langmuir-Blodgett thin films are often used to deposit ordered nanocomposites, however, this technique is inappropriate for multiple layer deposition of incompatible materials. Matrix-assisted pulsed laser evaporation (MAPLE) is a novel deposition technique for these hybrid structures, and has been utilized to demonstrate controlled polymer deposition for many materials on a variety of surfaces.^{2,3,4,5} In this paper, we will demonstrate MAPLE deposition of a variety of CQD/polymer nanocomposites on different substrates and compare the structural and optical properties of these films. CdSe CQDs will be suspended in the following conducting polymers for MAPLE deposition: poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV), cyano-substituted MEH-PPV (MEH-CN-PPV), poly(3,5-pyridinedyl), and poly(2,5-pyridinedyl). N-type, P-type, and semi-insulating GaAs, as well as glass, substrates will be used for the depositions to determine their influence on the structural and optical properties of the nanocomposites. Structural measurements will include atomic force microscopy (AFM) and transmission electron microscopy (TEM) to compare the structural variation of the MAPLE-deposited films, as well as dispersion phenomena of the embedded CQDs for different growth conditions. Optical characterization will include photoluminescence (PL) and Fourier transform infrared (FTIR) spectroscopies to study variations in the deposited films. MAPLE prepared

samples will be compared to similarly drop cast samples to demonstrate improved structural control without significant change in optical properties. Finally, a heterostructure of different, polymer/CQD nanocomposites will be deposited by MAPLE to demonstrate controlled deposition of different material systems. The structural and optical properties of this heterostructure will be compared to those of its constituent layers. The demonstration of such a multiple-layer, hybrid nanocomposite, thin film deposition will have important implications for future organic/inorganic photovoltaics. Sponsored by AFOSR and NSF. ¹Sun, B., et. al. (2005), *J. App. Phys.*, 97, 014914. ²Piqué, A., et. al. (1999), *Thin Solid Films* 355/356, 536. ³Wu, P. K., et. al. (2000) *Mat. Res. Soc. Symp. Proc.*, 617 j2.3. ⁴Toftmann, B., et. al. (2004), *Thin Solid Films* 453/454, 117. ⁵Bubb, D.M., et. al. (2004), *J. App. Phys.* 95, 2175.

Session C: III-Nitride Electronic Devices

Wednesday AM
June 20, 2007

Room: 102
Location: DeBartolo Hall

Session Chair: Michael Manfra, Lucent Technologies

10:00 AM Student

C1, High-Mobility Ultrashallow Pseudomorphic AlN/GaN Heterojunctions by MBE: *Yu Cao*¹; David Deen¹; Kejia Wang¹; Debdeep Jena¹; ¹University of Notre Dame

Few reports exist on the growth of ultrashallow (few nms) pseudomorphic AlN/GaN heterojunctions.¹ Even with a few nm of pseudomorphic AlN layers, the discontinuity in polarization across the heterojunction is expected to lead to a very high density 2-dimensional electron gas (2DEG) at the heterointerface. The absence of alloy scattering is expected to lead to high mobilities. The transport properties of thin AlN/GaN junctions and the scattering mechanisms limiting the 2DEG mobility have not been studied yet. In addition to obvious applications in high-transconductance, low-threshold voltage high-electron mobility transistors (HEMTs), the high-density, high-mobility 2DEGs at ultrashallow AlN/GaN heterojunctions can enable a variety of novel devices such as high-performance transparent biosensors, THz emitters, and other applications where 2DEGs buried a few nm from the surface is desirable. In this work, we report the transport and structural properties of such ultrathin pseudomorphic AlN/GaN heterojunctions grown by MBE, and identify the dominating scattering mechanisms. All growths were performed under metal-rich conditions at a RF Nitrogen plasma power of 150 W. The epitaxial AlN layer thickness was varied from 1 nm to 8 nm. AFM measurements showed very smooth morphologies with atomic steps around dislocation surface terminations, with a RMS roughness of ~0.3 nm for 2X2 micron scans for all samples except in the 8 nm AlN/GaN structure, where cracks were observed in the c-plane. 2DEGs were observed in Hall measurements for AlN thicknesses from 2 nm – 8 nm, but none was observed in the 1 nm AlN/GaN structure. The 2DEG sheet density increased with the thickness of the AlN epilayer – from $0.72 \times 10^{13} \text{ cm}^{-2}$ for an AlN barrier thickness of 2.0 nm to $3.3 \times 10^{13} \text{ cm}^{-2}$ for a barrier thickness of 5.0 nm, in quantitative agreement with a theoretical polarization-based electrostatic model. The 300K mobility was ~1200 cm^2/Vs , and it increased to ~4000-5000 cm^2/Vs at 77K with the barrier thickness between 2.4 nm and 4.0 nm. There was a clear drop of the 77K mobility for 2DEG densities higher than $3 \times 10^{13} \text{ cm}^{-2}$. To identify the scattering processes that limit the mobility, temperature-dependent Hall measurements were performed from 10 – 290 K. From a theoretical model, a quantitative explanation for the drop in mobility for thicker AlN barrier layers was found. The low-temperature mobility in the 2DEGs is limited entirely by interface roughness scattering at high 2DEG densities. The 300K mobility was limited by combined interface roughness and polar optical phonon scattering. The high 2DEG mobilities and the very high sheet densities observed point towards the fact that coherently strained, thin epitaxial AlN layers were successfully grown on GaN, opening up a number of possible new applications. ¹I. P. Smorchkova et al., *Appl. Phys. Lett.* 77, 3998 (2000).

10:20 AM Student

C2, Properties of GaN Buffer Layers on 6H-SiC Grown by Ammonia Molecular Beam Epitaxy for High Electron Mobility Transistors: *Andrea Corrion*¹; Christiane Poblentz¹; Rongming Chu²; Likun Shen²; F. Recht²; C. Suh²; Umesh Mishra²; Jim Speck¹; ¹University of California, Santa Barbara, Materials Department; ²University of California, Santa Barbara, Electrical and Computer Engineering Department

Ammonia molecular beam epitaxy is an attractive growth technique for III-nitride semiconductors. While plasma-assisted molecular beam epitaxy (PA-MBE) has been more widely studied, it requires metal-rich growth conditions for optimal film properties, resulting in the formation of metal droplets, nonuniformity, increased leakage currents, and restricted growth temperatures. Ammonia MBE, on the other hand, has been shown to allow growth at V/III ratios of greater than one. The excess group V flux suppresses decomposition, allowing higher growth temperatures, which has been shown to be critical in reducing impurity incorporation and threading dislocation (TD) densities. We report on the effect of growth conditions on the structural, morphological, and electronic properties of these buffer layers for high-electron mobility transistors (HEMTs), and demonstrate a HEMT with 7.1 W/mm output power. Growth rate, V/III ratio, growth temperature, and film thickness were varied in order to optimize TD density and surface morphology. All ammonia GaN growth was performed for effective V/III > 1, confirmed by a linear dependence of growth rate on gallium flux for the range of growth conditions used. Growth rates were varied from 125–815 nm/hr, while V/III ratios were varied from 3000–460. Growth temperatures were varied from 745–825°C as measured by a calibrated pyrometer. It was found that decreasing growth rates, increasing growth temperatures, and increasing V/III ratios resulted in decreasing surface roughness. The effect of the growth conditions on TD density was also investigated. Cross-sectional TEM revealed that the TDs were primarily pure edge dislocations with burgers vector of type [11-20]. The TD density decreased with increasing growth temperature and decreasing V/III ratio, which resulted in enhanced surface roughness and a transition from a two- to a three-dimensional growth mode. A two-step buffer was developed in which the first step was grown under high temperature, low V/III ratio conditions to achieve low dislocation density, resulting in 25% reduction in dislocation density. A three-micron thick sample with the two-step buffer had a TD density of $3 \times 10^9 \text{ cm}^{-2}$, among the lowest values reported for MBE GaN on SiC. Ammonia MBE AlGaIn/GaN HEMTs were fabricated, and an output power of 7.1 W/mm with a PAE of 49% was achieved at 4 GHz and a drain bias of 50 V. The HEMTs were found to have very low buffer leakage, resulting in a high breakdown voltage of >200 V. The 2DEG density and room temperature mobility were $8.5 \times 10^{12} \text{ cm}^{-2}$ and $1350 \text{ cm}^2/\text{Vs}$, and the gate-drain breakdown was 200 V. The vertical reverse-bias leakage current in PA-MBE and ammonia MBE samples was compared, and the electrical activity of threading dislocations was investigated to explain differences in leakage.

10:40 AM

C3, Extraction of Transport Dynamics in AlGaIn/GaN HFETs through Free Carrier Absorption: *Yuh-Renn Wu*¹; John Hinckley²; Jasprit Singh²; ¹National Taiwan University; ²University of Michigan

The importance of AlGaIn/GaN HFETs in high power high frequency applications is now well established. However, detailed information on high field mobilities, velocity-field relations, carrier temperature, momentum and energy relaxation times are not available. This is partly due to the difficulties of making these measurements directly and partly due to difficulties in interpreting device results that could provide these transport parameters. In this paper we carry out theoretical simulations based on Monte Carlo techniques to show that transport dynamics can be effectively extracted through free carrier absorption with input frequencies ranging from 50 GHz to a few THz. Using short pulses of millimeter waves, it is possible to obtain the velocity-field curve by fitting the absorption spectrum without heating the device. The technique measuring the free carrier absorption has been proposed theoretically and experimentally to study the carrier dynamics in other material systems such as GaAs, Si, etc.^{1,2} Recently there has been an experimental study on Ga structures³ showing the potential use of carrier absorption in obtaining transport parameters. In this paper, free carrier absorption done at (i) different input intensities; (ii) different dc bias values; and (iii) different polarization (i.e. ac field parallel and perpendicular to the

2DEG plane) can provide detailed information not only on the mobility and velocity-field relation but also carrier temperature and relaxation times. We show this by solving the classical transport equation and then verify the results through Monte Carlo simulations. In the AlGaIn/GaN system the presence of the non-linear “hump” in the velocity-field relation followed by a peak in velocity and negative resistance region are all reflected in carrier absorption done under dc bias conditions. With the model presented it would be possible to extract carrier dynamics from experimentally measured results. Our work suggests that free carrier absorption experiments on AlGaIn/GaN HFETs would provide important transport information, which would be very useful in device design and modeling. ¹H. Jiang, J. M. Hinkley, and Jasprit Singh, IEEE, J. of Quantum Electronics, 33, p1779, 1997. ²N. A. Kabir, Y. Yoon, J. R. Knab, J.-Y. Chen, A. G. Markeiz, J. L. Reno, J. Sadofyev, S. Johnson, Y.-H. Zhang, and J. P. Bird, Appl. Phys. Lett., 89, p132108, 2006. ³T. R. Tsai, S. J. Chen, C. F. Chang, S. H. Hsu, T. Y. Lin, C. C. Chi. Optical Express, 14, 4898, 2006.

11:00 AM

C4, Scanning Ion Probe Studies of Silicon Implantation Profiles in AlGaIn/GaN HEMT Heterostructures: Martin Kocan¹; Matt Kilburn¹; Ian Fletcher¹; Felix Recht²; Lee McCarthy²; Umesh Mishra²; Brett Nener¹; *Giacinta Parish*¹; ¹University of Western Australia; ²University of California, Santa Barbara

Ion implantation, an established technique for mature semiconductor technologies such as Si and GaAs, should also lead to many advantages for III-nitride semiconductor devices such as selective lateral doping, formation of non-annealed ohmic contacts, creation of various devices on a single wafer and non-etch-based device isolation. In this study, a CAMECA nanoSIMS 50 ion microprobe was used to investigate lateral doping profiles in AlGaIn/GaN HEMTs with silicon-implanted source/drain regions. The nanoSIMS ion beam is only approximately 50nm in diameter, allowing high resolution dopant mapping. Previous transfer length method (TLM) measurements had shown that the total contact resistance to the channel of source/drain implanted AlGaIn/GaN HEMTs consists of three components: the contact resistance of the metal to the implanted layer, the sheet resistance of the implanted semiconductor material and an additional resistance, R_T . This additional resistance does not seem to come from the non-implanted channel or from the implanted layer, but rather from a transition region such as the interface between implanted and non-implanted regions. Possible explanations include a 2D/3D transition resistance between source/drain and channel, or a depletion of the 2DEG adjacent to the implanted region, possibly caused by implantation damage to the AlGaIn. In this study, the lateral silicon profile was measured to see if any clues could be provided about the transition region. To achieve the desired profiles, $20 \mu\text{m} \times 20 \mu\text{m}$ 2D scans of various ions, including ²⁸Si, ²⁷Al, and ⁶⁹Ga¹⁴N signals, were obtained by rastering across the TLM device surface. Line profiles were then extracted from the 2D scans. The observed profiles showed definite broadening of the silicon implantation edge. In these devices, which were fabricated on the same wafer as the implanted source/drain HEMTs, the contacts to the implanted regions were recessed. Therefore, to validate the profiling, which had not been done before with this instrument, the silicon profile was compared at the recess etch edge and the implantation boundary. It was confirmed that the silicon signal decay observed at the implantation edge was due to the implantation broadening and not the instrument. The measured profiles were used to recalculate the resistances obtained with the TLM analysis, but it was found that simple geometrical adjustments did not account for the measured additional resistance R_T . To confirm this, the breadth of profile required to reduce the value of the R_T to zero was also calculated, and found to be much larger than what was observed. Therefore, the conclusions made here are well within the resolution of the nanoSIMS technique. Although incorporating the observed broadening into a simple resistance model cannot account for R_T , the implications of the broadening for other transition resistance explanations are currently under investigation.

11:20 AM Student

C5, A Study of Post-Bombardment Effects of Electronegative Ions on the Two-Dimensional Electron Gas Properties of AlGaIn/GaN Heterostructures: Anirban Basu¹; Vipan Kumar¹; Ilesanmi Adesida¹; ¹University of Illinois at Urbana-Champaign

AlGaIn/GaN high electron mobility transistors (HEMTs), in recent years, have emerged as exceptionally promising candidates for high-power, high-speed, and microwave low noise applications. While high performances have been readily achieved in depletion mode (D-mode) AlGaIn/GaN HEMTs, it is challenging to fabricate enhancement-mode (E-mode) AlGaIn/GaN HEMTs with high-performance characteristics including high transconductance, low on-resistance, low knee voltage, and large input voltage swing. Enhancement-mode AlGaIn/GaN HEMTs have advantages over D-mode HEMTs; these include reduced circuit complexity, the elimination of the negative-polarity voltage supply in some circuits leading to low power dissipation and reduced cost. An E-mode AlGaIn/GaN HEMT can be obtained by the control of the threshold voltage (V_{th}) that can be realized through the modulation of the energy band by implanting F- ions in the AlGaIn/GaN heterostructure using plasma treatment techniques.¹ The fluorine ions have a strong electronegativity and are negatively charged, effectively raising the potential in the AlGaIn barrier and the two-dimensional electron gas (2DEG) channel. Post-bombardment annealing has proven to be effective in annealing out the plasma-induced damages. A detailed study on the modulation of the mobility and sheet concentration of the 2DEG by the incorporated F- ions in the HEMT layer followed by annealing is still lacking. Such a study is imperative in understanding the behavior of the 2DEG transport and separating out the intrinsic electronic effects of the fluorine ions from the physical effects of low-energy ion bombardment. This will provide a critical basis for the optimum design of E-mode AlGaIn/GaN HEMTs. In this study, Hall measurement structures were fabricated on MOCVD-grown AlGaIn/GaN HEMT epitaxial layers. Ti/Al/Mo/Au ohmic contacts were formed on the Hall structures at 850°C. Windows were opened by photolithography on top of structures and the samples were then inserted in an RIE (reactive ion etching) system for CF₄ plasma bombardment at different self-bias voltages by adjusting RIE power. Results show unexpected simultaneous decrease in post-bombardment and post-annealed mobility and sheet concentration of the 2DEG. The behavior of fluorine ions inside the HEMT layer for different plasma bombardment voltages, different annealing temperature and different annealing time interval strongly influences the transport properties of the 2DEG. A comparative study of bombardment with other ions such as oxygen will be reported. Results from Hall measurements, Shubnikov-de Haas oscillation data and other microanalytical methods, such as secondary ion mass spectroscopy (SIMS), will be presented. Implications of such plasma treatment on device performance will be discussed. ¹Y. Cai, Y. G. Zhou, K. J. Chen, and K. M. Lau, IEEE Electron Device Lett. 26, 435–437 (2005).

11:40 AM

C6, Crystalline SiN_x Ultrathin Films Grown on AlGaIn/GaN by In-Situ Metalorganic Chemical Vapor Deposition: Toshiyuki Takizawa¹; Satoshi Nakazawa¹; Tetsuzo Ueda¹; ¹Matsushita Electric Industrial Company, Ltd.

Surface passivation by SiN_x film is inevitable for the high power operation of AlGaIn/GaN heterojunction field-effect transistors (HFETs) since it can effectively suppress the current collapse.¹ SiN_x deposited by Cat-CVD is reported to increase the sheet carrier density of AlGaIn/GaN as well.² In this paper, we present the deposition of ultrathin SiN_x film on AlGaIn/GaN in a metal organic chemical vapor deposition (MOCVD) subsequently after the epitaxial growth. We experimentally confirm the crystallization of the “in-situ” SiN_x which drastically increases the sheet carrier concentration of the underlying 2DEG. The in-situ SiN_x is deposited using SiH₄ and NH₃ in a MOCVD chamber after the growth of 8-nm-thick Al_{0.4}Ga_{0.6}N / 2.5-μm-thick GaN on (0001) sapphire substrate. The few nm-thick SiN_x increases the sheet carrier concentration from the unpassivated one’s 1×10¹³cm⁻² to 2×10¹³cm⁻² as is observed for the passivation by Cat-CVD. High resolution cross-sectional transmission electron microscopy (HR-TEM) reveals that the in-situ SiN_x exhibits the crystalline structure with the lattice constants of $a \sim 3.2 \text{ \AA}$ and $c \sim 2.4 \text{ \AA}$ which are quite different from those of well-known Si₃N₄ crystal structures such as β-phase. First-principles calculation is carried out to investigate the most stable crystal structure of the SiN_x, in which it is demonstrated that introducing defects in crystalline structure

gives more stable structure. In addition, high-resolution electron energy loss spectroscopy (EELS) study confirms the abrupt interface between in-situ SiN_x and AlGaIn. In conclusion, formation of crystalline SiN_x by in-situ MOCVD on AlGaIn/GaN is demonstrated. The lattice constants are different from the well-known values for conventional crystalline SiN_x. The crystalline SiN_x effectively increases the sheet carrier concentration in the 2DEG, which would be promising for high power and microwave applications of AlGaIn/GaN HFETs. ¹J.A.Mittereder et al., Appl.Phys.Lett. 83, 1650(2003). ²M.Higashiwaki et al., Phys.Stat.Sol.(a) 203, 1851(2006).

Session D: Spin in Low-Dimensional Systems

Wednesday AM
June 20, 2007

Room: 155
Location: DeBartolo Hall

Session Chair: Craig Pryor, University of Iowa

10:00 AM Student

D1, Transport in Room-Temperature Ferromagnetic (Ga,Mn)N Nanowires: Moon-Ho Ham¹; Jae-Min Myoung¹; ¹Yonsei University

The (Ga,Mn)N nanowires with various Mn concentrations of 0.5–10% were synthesized by varying the separation between MnCl₂ and GaN powders under NH₃ gas flow via vapor-liquid-solid method. The x-ray diffraction and transmission electron microscopy studies revealed that all the (Ga,Mn)N nanowires were single-crystalline without secondary phases. The ferromagnetic ordering exceeding room temperature was found for all the (Ga,Mn)N nanowires and was dependent on Mn concentration in the (Ga,Mn)N nanowires with a maximum at Mn concentration of 5%. Furthermore, the (Ga,Mn)N nanowire field-effect transistors were fabricated in back-gated structure with 300 nm-thick SiO₂ gate dielectric in order to investigate transport properties of the nanowires. The (Ga,Mn)N nanowires configured as field-effect transistors exhibited a conductivity conversion from n type to p type with increasing Mn concentration and the good electrical properties with on/off current ratio of ~102 and subthreshold slope of 1.9–2.2 V/dec. In particular, the (Ga_{1-x}Mn_x)N nanowires with x = 5% which had the highest magnetic moment were found to be a p-type conductivity with a hole concentration of 10¹⁷ cm⁻³. It strongly support that the magnetic properties in the (Ga,Mn)N nanowires depend not only on the Mn concentration but also on the carrier type and concentration. Moreover, for the p-type (Ga_{1-x}Mn_x)N nanowires with x=5%, the negative magnetoresistance was found up to room temperature and found to gradually increase with decreasing temperature, reaching ~3% at 10 K. For the undoped GaN nanowires as a reference sample, a linear M-H characteristic with a negative slope and no negative magnetoresistance were observed. It demonstrate that the ferromagnetic ordering and magnetotransport in the samples doped with Mn does not come from the catalysts and substrates but is ascribed to the (Ga,Mn)N nanowires themselves due to Mn incorporation. These results suggest that the (Ga,Mn)N nanowires and their field-effect transistors could enable to apply not only nanoscale electronic devices and but also nanoscale spintronic devices.

10:20 AM Student

D2, Calculation of Lande g-Factors and Comparison with Experiment for III-V Nanowhisker Quantum Dots: Amrit De¹; Craig Pryor¹; ¹University of Iowa

We have calculated Lande g-factors for electrons confined in nanowhisker quantum dots (NWQDs) consisting of a InP/InAs/InP quantum well embedded in a <111> oriented InAs nanowisker. Confinement energies and wavefunctions for valance and conduction band states were calculated as a function of dot size, and corresponding Lande g-factors were calculated. The calculated g-factors are in good agreement with experimental measurements on a variety of geometries. These differ markedly from g-factors obtained from bulk formulas with energies modified to match that of the NWQD states. This provides strong confirmation of the effect on g of angular momentum quenching. The calculations were carried out using 8-band strain-dependent

k.p theory in the envelope-function approximation using a finite difference technique on a real space grid.

10:40 AM Student

D3, Exchange Coupling in Quantum Wire Quantum Dots: *Lingxiao Zhang*¹; Dmitriy Melnikov¹; Jean-Pierre Leburton¹; ¹University of Illinois at Urbana-Champaign

The exchange coupling J , defined as the energy difference between the lowest singlet and triplet two-electron states, plays the central role in solid state spin-qubit quantum computing.¹ Recently, InAs quantum wire quantum dots (QWQD) emerged as a novel hardware scheme for engineering J due to its small predefined lateral size (diameter of wire ~ 50 nm) and reduced inter-dot separation (down to 20 nm).² In this work, we perform a theoretical study of the exchange coupling in two coupled QWQDs. In the lateral dimensions (x and y), parabolic confinement with cylindrical symmetry is used for each quantum dot while the coupling of the dots in the vertical z -direction is simulated by a coupled Gaussian potential. The confinement is tunable via a magnetic field applied in the z -direction. To compute the singlet and triplet energies as well as the two lowest single-particle energies (their difference gives the tunnel coupling $2t$) in this inherently 3D system, we utilize the variational Heitler-London approach³ in which the inter-electron separation and the wave function localization radii are treated as adjustable parameters determined from the energy minimization. With this method, we show that both the exchange coupling and the tunnel coupling decrease with increasing inter-dot separation d . We also identify two distinct regions in the dependences of J and $2t$: at large inter-dot separations, these quantities decay exponentially with d , while at smaller values, this decrease is linear, corresponding to the transition from the double dot to the effective single dot configuration. We also obtain that J decreases as the wire's diameter D is made smaller. However, this decrease of J is faster for the intermediate values of d than for small or very large inter-dot separation values. Calculations with the magnetic field oriented in the z -direction confirm that the magnetic field changes the effective diameter of the wire, and as such, can be used to tailor the exchange coupling in QWQD systems. Finally, analysis of the expectation values of the Coulomb interaction (Coulomb energy) reveals that for large d , both singlet and triplet Coulomb energy decrease monotonically with D , while for smaller values singlet Coulomb energy has a local maximum at small D , whereas triplet Coulomb energy always decreases monotonically with D . ¹D. Loss and D. P. DiVincenzo, Phys. Rev. A 57, 120 (1998). ²M. T. Björk et al., Nano. Lett. 9, 1621 (2004). ³W. Heitler and F. London, Z. Phys. 44, 455 (1927).

11:00 AM

D4, Transport Spectroscopy in a Few-Electron Quantum Dots: *Dmitriy Melnikov*¹; Jean-Pierre Leburton¹; ¹University of Illinois at Urbana-Champaign

Transport properties of a few-electron single vertical quantum dot (QD) in external magnetic fields are investigated theoretically. By solving the many-electron Schrodinger equation and computing one-particle Green functions (overlap), we are able to calculate the tunneling current through the double-barrier QD structure for finite values of the source-drain bias. Our simulations of the quantum current reveal a highly complex interplay between tunneling barrier permeabilities, electron spin effects, degeneracies among energy levels, non-equilibrium occupancies, and wave function overlaps. We find that correlations among many-particle states give rise to a multitude of internal electronic excitations that produce rich current spectra which cannot be explained by the eigenenergy diagram. In particular, we show that depending on the applied bias, the dominant changes in the current through the N -electron QD can be caused not only by the involvement of excited N -electron states in the transport process but can also be due to excitations in the $(N-1)$ -electron system. The latter type of excitations have significant implications in the interpretation of the current spectra as it influences the transport through the QD, and as such, should be taken into account when extracting various quantities of physical interest, such as the exchange energy, from the experimental data. Overall, the computed current spectra are found to be in a good agreement with available experimental data [L. P. Kouwenhoven, et al., Science 278, 1788 (1997)].

11:20 AM Student

D5, Enhanced Spin-Orbit Interaction in Strained InGaAs/AlGaAs Heterostructure for Spin Transistors: *Takashi Matsuda*¹; Kanji Yoh¹; ¹Hokkaido University

The estimation of the spin-orbit interaction and its control in semiconductor quantum wells has been of significant interest after the proposal of spin-FET by Datta & Das.¹ Importance of conduction band discontinuities in the quantum well was pointed out as the source of the energy shift by Pfeffer and Zawadzki² in InGaAs/InAlAs heterostructures grown on InP, as opposed to the conventional interpretation that the spin-orbit interaction is proportional to the average electric field in a well.³ We have designed and fabricated pseudo-morphic InGaAs channel structures with high indium content and showed enhanced spin-orbit interaction. The fabricated In_{0.9}Ga_{0.1}As heterostructures contain high sheet carrier concentration of $2 \times 10^{12} \text{cm}^{-2}$ which make the peak of the electron wave function lie on the conduction band discontinuity between main channel and front subchannel. The enhancement of spin-orbit interaction was verified experimentally and confirmed theoretically by la Zadski. Sample 1 has In_{0.9}Ga_{0.1}As channel of 50A thickness and sample 2 does InAs channel of 40A thickness. Mobility and carrier concentration of sample 1 and sample 2 are $76000 \text{cm}^2/\text{Vs}$, $1.6 \times 10^{12} \text{cm}^{-2}$ and $58000 \text{cm}^2/\text{Vs}$, $2.0 \times 10^{12} \text{cm}^{-2}$, respectively at 3.8K. Shubnikov de Haas (SdH) oscillation was measured to estimate Rashba coefficient α which indicate the magnitude of the spin splitting as $\Delta E = 2\alpha|k_x|$. Rashba coefficient could be modulated, from $52 \times 10^{-12} \text{eVm}$ to $66 \times 10^{-12} \text{eVm}$ for sample 1 and from $50 \times 10^{-12} \text{eVm}$ to $70 \times 10^{-12} \text{eVm}$ for sample 2 by applying gate voltage. These values turned out to be extremely large compared with the value, $30 \times 10^{-12} \text{eVm}$, usually reported for InAs-based HEMTs in conventional simple quantum well structure whose wavefunction lies in the center of the well. Theoretical estimation² was carried out to verify such an enhanced Rashba coefficient observed experimentally. The estimation showed the Rashba coefficient of sample 1 is $24 \times 10^{-12} \text{eVm}$, and the effect of band discontinuity (α_1) contributes $12 \times 10^{-12} \text{eVm}$ and average electric field (α_2) contributes $13 \times 10^{-12} \text{eVm}$ to it. The Rashba coefficient of sample 2 is $46 \times 10^{-12} \text{eVm}$ and $\alpha_1 = -1 \times 10^{-12} \text{eVm}$ and $\alpha_2 = 47 \times 10^{-12} \text{eVm}$. Control sample of In_{0.81}Ga_{0.19}As HEMT, whose wavefunction peak lies in the well, was fabricated and the Rashba coefficient was estimated to be $21 \times 10^{-12} \text{eVm}$ by both SdH analysis and theoretical calculation. In conclusion, we have proposed and verified InAs (or InGaAs) channel HEMT structure with an enhanced spin-orbit interaction. The result suggests a new direction to achieve short channel Datta-Das spin transistor which is a key to make the device work by minimizing spin relaxation in the channel. ¹S.Datta and B.Das, Appl. Phys.Lett. 56, 665 (1990). ²P.Pfeffer and W.Zawadzki, Phys. Rev. B, 59, R5312 (1999). ³E.A.de Andrada e Silva et al., Phys. Rev. B, 50, 8523 (1994).

11:40 AM

D6, Late News

Session E: Non-Destructive Testing

Wednesday AM
June 20, 2007

Room: 131
Location: DeBartolo Hall

Session Chairs: Andrew Hoff, University of South Florida; Kurt Eyink, U.S. Air Force Research Laboratory

11:00 AM

E1, GaSb(001) Surface Reconstructions Measured at the Growth Front by Surface X-Ray Diffraction: *Brad Tinkham*¹; Oleksandr Romanyuk¹; Vladimir Kaganer¹; Wolfgang Braun¹; Klaus Ploog¹; Masamitsu Takahashi²; Toshiyuki Kaizu²; Junichiro Mizuki²; ¹Paul Drude Institute; ²Japan Atomic Energy Agency

GaSb is a narrow band gap semiconductor commonly used as a substrate for the growth of lasers and photodetectors operating in the long wavelength regime. The growth kinetics and surface structure on GaSb(001) is less understood than for its counterparts, GaAs(001) and InAs(001). The GaSb(001) surface exhibits two distinct surface symmetries that are a

function of Sb flux and surface temperature. At low temperature and/or high Sb flux, a (1x5) surface reconstruction is present. STM measurements have indicated two different structural arrangements, namely c(2x10) and (2x10) unit cells that could produce this (1x5) diffraction pattern. These structures have three layers and two layers of Sb on the surface, respectively, and are both in violation of the electron counting rule, which is a guiding principle, based on bonding configurations that is used to determine if structures are energetically favorable. For the lower Sb-coverage surface, which appears at higher temperature and lower Sb-flux, a (1x3) RHEED pattern is observed. There are several proposed models for this phase, all of which obey the electron counting rule. From STM measurements, it has been concluded that the atoms arrange in a (4x3) unit cell, with Sb-Sb dimers and Ga-Sb heterodimers running along the [-110] direction. Although two distinct (4x3) phases are predicted to exist (alpha and beta), STM images taken at room temperature always show a coexistence of the two phases. We have employed x-ray diffraction, in situ, to measure the aforementioned (1x5) and (1x3) surface phases under technologically relevant growth conditions. X-ray diffraction has several distinct advantages over other structural probes, most notably that the diffraction can be analyzed by kinematical diffraction theory, which allows a relatively straightforward quantitative analysis. We have measured over 60 inequivalent in-plane surface reflections on each surface phase and over 150 total reflections on each surface total. From this data we have calculated 2D Patterson functions, the peaks of which represent inter-atomic distances weighted by the product of the number of electrons in the individual atoms. The Patterson functions have been calculated for all competing models and are compared with our data generated from in situ measurements. For the (1x3) phase we obtain good agreement between our data and the heterodimer models proposed in recent experimental and theoretical work. Our measurements on the Sb-rich (1x5) phase provide evidence that the structure under growth conditions is in fact different than the models determined from STM. We discuss reasons for this discrepancy as well as our progress in obtaining 3D models for these reconstructions that include surface relaxations and subsurface rearrangement.

10:20 AM

E2, X-Ray Reflectivity Based Metrologies for the Development of Metamorphic Semiconductor Device Structures: Benjamin Poust¹; Vincent Gambin¹; Benjamin Heying¹; Michael Lange¹; Rajinder Sandhu¹; Patrick Chin¹; Mark Goorsky²; ¹Northrop Grumman; ²University of California, Los Angeles

X-ray reflectivity can be used to determine the thickness of deposited thin films. Measurement of the interference pattern is straightforward, but extracting film thickness(es) can be challenging. A sophisticated approach is to fit the data using dynamical theory based on the distorted wave Born approximation. This works extremely well for most applications, but non-ideal samples present a challenge. Problems arise when, for example, an unexpected compound forms at an interface, or when an oxide of unknown thickness contributes to the interference effect. If simulating the intended structure yields a poor fit, the researcher must guess at how to alter the model to obtain a useable fit and runs the risk of drawing spurious conclusions. An alternative is to apply Fourier transforms (FTs). This is a powerful technique that complements dynamical modeling well. An FT power spectrum peak represents the frequency or period length of an interference oscillation. When applied to x-ray scatter data with film thickness fringes, FT peak positions represent layer thicknesses. However, a few properties of x-ray scatter data severely limit the effectiveness of Fourier transforms. In large part, this has limited the popularity of FT analysis with x-ray scatter data. A new enhancement technique addressing these challenges is presented here. Discrete Fourier transforms (DFTs) and their application to x-ray scatter data are discussed in terms of the mathematics, challenges inherent to x-ray scatter FTs, and enhancement techniques in the literature. The enhancement technique presented here is demonstrated using two emerging metamorphic technologies: AlGaIn/GaN and AlSb/InAs based mHEMTs. X-ray reflectivity scans of AlGaIn/GaN based mHEMTs were analyzed to determine the AlGaIn barrier thickness. The results were confirmed with STEM measurements of the barrier layer thickness. While the AlGaIn/GaN mHEMT is a relatively simple structure yielding straightforward interpretation, the task of analyzing layer thicknesses in the AlSb/InAs mHEMT structure is complicated due to the number of layers contributing to the interference pattern. Fourier transforms of dynamical simulations were used as a guide to interpreting the

measured x-ray reflectivity FT power spectrums. Channel and upper AlSb barrier thicknesses were determined to be very close to the target values. The donor layer thickness was determined to be very close to the target value of 1.2 nm. The sum of the cap, hole barrier, and upper electron barrier layer thicknesses was determined to be somewhat thinner than the sum of the target thicknesses in some cases. Enhanced Fourier analysis is shown to be extremely effective in extracting layer thicknesses from reflectivity scans with excellent correlation to traditional analysis and STEM measurements.

10:40 AM Student

E3, Temperature Dependent Stress Distribution in Heterogeneous Wafer Bonded Structures by Double Crystal X-Ray Diffraction Imaging: Michael Jackson¹; Sumiko Hayashi¹; Mark Goorsky¹; ¹University of California, Los Angeles

Thermal expansion differences between electronic materials used in modern heterogeneous device applications, such as three dimensional IC's, can lead to a limited operating temperature range before high stresses inhibit device performance. Double crystal x-ray diffraction imaging and a variable temperature stage are employed to visualize the stress distribution in heterogeneous wafer bonded layers. A sequence of superimposed diffraction images taken at slightly different incident beam angles reveals the variation of localized lattice orientation caused by thermal or residual stresses. By employing Stoney's equation along with a correction factor presented by Klein, these curvature values can be converted into quantitative stress values. This technique is uniquely qualified for determining the deformation of crystalline materials as it does not depend on surface topographical features as optical interferometry techniques do. The technique is demonstrated using test structures. The stress distribution in InP layers transferred to a silicon substrate at room temperature exhibits an anticlastic deformation, with different regions of the wafer experiencing different signs of curvature. Measurements at elevated temperatures ($\leq 125^\circ\text{C}$) reveals that differences in thermal expansion coefficients dominate the stress and that interfacial particulates introduce very high local stress gradients that increase with increased temperature. For thinned GaAs substrates (100 μm) bonded using patterned metal interlayers to a separate GaAs substrate at $\approx 200^\circ\text{C}$, residual stresses are produced at room temperature due to local stress points from metallization contacts, and these complex stress patterns can be observed using the diffraction imaging technique. The double crystal x-ray diffraction imaging (topography) technique employed here uses a miscut Si (224) first crystal for beam collimation and expansion. For GaAs, the (115) reflection provides an excellent Bragg angle match and produces a diffraction image with a divergence of only a few arcsec. Therefore, any curvature-inducing features greater than this value can be quantified with a series of diffracted intensity images. These images can be collected on the same film or on separate films and overlaid using digital imaging techniques.

11:00 AM Student

E4, Indium Adlayer Kinetics on Gallium Nitride (0001) Surfaces: Monitoring Indium Segregation and Precursor Mediated Adsorption: Soojeong Choi¹; Tong-Ho Kim¹; Scott Wolter¹; Henry Everitt¹; April Brown¹; Maria Losurdo²; Giovanni Bruno²; ¹Duke University; ²MIP-Consiglio Nazionale delle Ricerche

Indium is an important constituent of the III-N semiconductor system with the highest atomic size and weight of all the group III metallic components. As compared to kinetic studies of gallium on GaN surfaces, the behavior of indium on GaN surfaces is still under investigation, even though it is empirically observed that indium acts as a surfactant for III-N material growth, and segregates during InGaIn quantum well growth. In this work, we study indium adsorption/desorption from a GaN (0001) template for indium fluxes in the range 4.96×10^{-9} – 7.59×10^{-7} Torr, and for substrate temperatures in the range 630–688°C. A thin adsorbent adlayer coating a semiconductor surface changes the relative amplitude ratio ($\tan\Psi$) and phase (Δ) of the parallel and perpendicular components of reflected light. Since indium has metallic characteristics, free electrons in the indium layer shield the transmitted electric field. This high absorption with respect to the substrate enhances the change of the two ellipsometric angles (Ψ and Δ), which affects the pseudo-dielectric function of a metal/semiconductor system. In particular, the variation of the imaginary part of the pseudo-dielectric function linearly depends on adlayer thickness, so that the adsorption/desorption processes

can be characterized from the variation of $\langle e_2 \rangle$ measured with spectroscopic ellipsometry (SE) at a photon energy 3eV. As in the case of the gallium deposition on GaN surfaces,¹ indium also has a critical thickness of ~2ML, and further deposition after this bilayer formation induces excess indium forming droplets which can act as a reservoir for the wetting layer. The indium wetting layer shows two stable states at around 1ML, and 1.7ML-2ML in the temperature range of 630-688°C. At the beginning of each ML formation, a flux offset is observed in the adsorption rate, which implies that different kinetics governs the nucleation formation. To explain the offset and observed non-exponential decay of the wetting layer, one model is suggested. The precursors or nuclei of the wetting layer bonds with the dangling bonds of the gallium atoms terminating the surface, and after formation of the nuclei, incoming indium atoms interact primarily with the nuclei. Preferable bonding formation with the nuclei supports the observed indium segregation. From the desorption curves, the activation energy was derived for the nuclei and wetting layers separately for the 1st and 2nd ML, here the activation energy of nuclei of 1st ML is around 2.04eV much lower than the desorption activation energies of 1st ML(2.64eV), 2nd ML nuclei (2.33eV), and 2nd ML(2.53eV), which are close to the bulk indium sublimation energy, 2.52eV. ¹Appl. Phys. Lett. 89, 181915 (2006).

11:20 AM Student

E5, Fast Corona-Voltage Metrology Characterization of 3C-SiC Oxide Structures: Eugene Short¹; Ian Haselbarth¹; Elena Oborina¹; Stephen Sadow¹; Catherine Moisson²; Andrew Hoff¹; ¹University of South Florida; ²NOVASiC

Oxide-semiconductor electrical characteristics are important to the development of future electronic device applications regardless of the component materials. We present the first results of capacitance-voltage characterization of oxide-3C-SiC-Silicon structures obtained using non-contact corona-voltage metrology. This important metrology method is common in the silicon IC industry and has been modified in our laboratory to facilitate its application to SiC materials. The method is quick, requires no device fabrication or thin film applications, and may be applied at selected points in a sequence of processes. In this work oxide characteristics were obtained with afterglow oxides grown following three different substrate material processes. These included the 3C-SiC deposition on silicon in our laboratory, after a subsequent chem-mechanical polishing of the same deposited 3C layer, and following sacrificial oxidation of the polished substrates. The 3C hetero-epitaxial films were grown in a hot-wall CVD reactor and were nominally 10 to 12 microns thick with resistivity from $4 \times 10^{15} \text{ cm}^{-3}$ to $1.7 \times 10^{16} \text{ cm}^{-3}$. This n-type material was oxidized at 850°C in an afterglow chemical reactor at 1 Torr total pressure to a nominal electrical oxide thickness in the range of 30 nm to 35 nm. All of the C-V characteristics obtained demonstrated a negative value of flatband voltage, V_{fb} , position varying about -4V depending on stress of the structure in accumulation. For reference typical results obtained using n-type 4H-SiC substrates exhibit V_{fb} values in a positive voltage range from 1 to 2 volts. Therefore these oxide-3C structures appear to have positive charge at the interface compared to typical 4H structures. In addition all C-V characteristics on the 3C material demonstrate an increased trap density near the conduction band edge. This latter feature is reduced by a factor of two following CMP of the 3C substrate. Otherwise the fundamental behavior of the capacitance-voltage characteristics were nominally similar between as-grown epi and following polish and sacrificial oxidation. The breakdown field reliability of the oxide was not a subject of this work but would likely have improved as a result of the CMP processing. These results demonstrate the utility of the corona-voltage approach in the characterization of new material processes. Detailed electronic characteristics were obtained on the same substrates following specific material processing steps and demonstrated subtle effects of the processing on the resulting oxide-semiconductor structures.

11:40 AM

E6, Photoluminescence Study of Self-Assembly of Heterojunction Quantum Dots(HeQuaDs): Kurt Eyink¹; David Tomich¹; Shyam Munshi¹; Bruno Ulrich¹; ¹U.S. Air Force Research Laboratory

Recently quantum dots (QDs) have been the topic of extensive research. Unique properties arise in QDs due to a combination of the localized nature of their wavefunctions and a singularity in the associated density of states.

Many strained III-V semiconductor film-substrate systems form QDs via a self-assembly process by means of a Stranski-Krastanov process. The strain relief responsible for the 3D nucleation causes a variation in the in-plane lattice constant which allows subsequent QD layers separated by thin spacer layers to be vertically stacked. Recently this concept has been extended to allow the formation of a heterojunction quantum dot (HeQuaD). In this structure an initial self-assembled QD (SAQD) is formed and then a different similarly strained material is nucleated on the initial SAQDs forming a crown on the underlying QD. This crown is also of a size appropriate to cause quantum confinement. In particular a stack of 4 layers of a HeQuaD structure of a GaSb crowned InAs SAQD on GaAs with GaAs spacer layers has been formed. The top HeQuaDs have been left uncapped to allow AFM analysis of the morphology. Photoluminescence of the HeQuaD has 3 peaks at ~0.95eV, 1.15eV, and 1.35eV. We have measured the intensity and temperature dependence of these PL peaks.

Session F: Germanium and Silicon Nanowires

Wednesday PM
June 20, 2007

Room: 126
Location: DeBartolo Hall

Session Chairs: Ray Tsui, Motorola Laboratories; Timothy Sands, Purdue University

1:30 PM

F1, Germanium Nanowires: Growth and Applications: Tong Wang¹; Lauren Klein¹; Eric Garfunkel¹; ¹Rutgers

We report on the structure, chemistry and properties of germanium nanowires grown via vapor-liquid-solid methods in a hot-wall chemical vapor deposition reactor. The diameter, density, and length of the nanowires are regulated by growth conditions (T, P, t, and Au nanoparticle size and density). Directional growth is controlled using epitaxy on single-crystal Si and Ge, aided by appropriate etch chemistries. In order to prevent re-oxidation of the nanowires after removal of the unstable native oxide, we have investigated various chemical passivation methods, including chlorination, H-termination, and thiol and alkene passivation. These chemistries are also used to facilitate further surface functionalization and ohmic formation, and to improve device electrical performance. Another more robust passivation approach is to form stable oxides; toward this end we have explored atomic layer deposition of high-k dielectric materials such as HfO₂. The nanowires and their coatings have been characterized by scanning and transmission electron microscopies, x-ray photoelectron spectroscopy, energy dispersive x-ray spectroscopy, x-ray diffraction, Rutherford backscattering spectrometry, and Fourier transform infrared spectroscopy. Use of the Ge nanowires in several device applications will be reported. The nanowires were grown or dispersed for fabrication of single nanowire field effect transistor, sensors, solar cells, and multi-nanowire thin-film-transistors.

1:50 PM Student

F2, Experimental and Theoretical Transport Characterization of Germanium Nanowires: Paul Leu¹; Makoto Koto¹; Svizhenko Alexei¹; Terry Hou¹; Kyeongjae Cho²; Paul McIntyre¹; ¹Stanford University; ²University of Texas-Dallas

Germanium nanowires (NWs) are a promising material for electronic and photonic devices due to the high carrier mobilities of Ge and the low temperatures required for Ge NW growth. We demonstrate an approach to integrate $\langle 111 \rangle$ Ge NWs into vertical arrays suitable for programmable interconnects and sensors. The transport properties of these Ge NWs as a function of length, diameter, and surface are characterized by experiments and theory. Ge NWs are heteroepitaxially grown vertically from Au catalysts dip coated onto a degenerately doped $\langle 111 \rangle$ Si substrate. Silicon dioxide is conformally deposited by plasma enhanced chemical vapor deposition around the vertical NWs to isolate and provide mechanical stability to the wires, followed by chemical mechanical polishing to planarize the structure. The tips of the NWs are exposed and can be contacted and electronically

characterized through the deposition of a top metal layer contact or with a conductive atomic force microscope. We compare trends in the experimental electrical transport properties of Ge NWs with simulation results from a non-equilibrium Green's function technique within an sp3d5s* tight-binding approximation.

2:10 PM Student

F3, Manganese-Mediated Growth of Ge/Mn₃Ge_{1-x} Nanowire Heterostructures: *Jessica Lensch*¹; Eric Hemesath¹; Francisco Lopez¹; Lincoln Lauhon¹; ¹Northwestern University

Research on impurity-mediated growth of one-dimensional materials, particularly semiconductor nanowires, has led to a wealth of interesting structures with varying degrees of potential for use in nanostructured materials and devices. Novel properties and device functions are most likely to arise from the controlled fabrication of heterophase nanostructures where the variations in phase and composition are controlled on the smallest length-scales. Here we report the growth of novel Ge/Mn₃Ge_{1-x} nanowire heterostructures with potential for use as one-dimensional spin-injectors/spin-filters. Mn particles were formed on SiN substrates via chemical vapor deposition of tricarbonyl cyclopentadienyl manganese (TCMn) at 300-400°C. Exposure of the Mn particles to germane resulted in the growth of germanium nanowires at temperatures ~400°C below the lowest Ge-Mn eutectic temperature. Nanowires with diameters of 10-25 nm and growth rates of up to 200 nm/min have been observed by scanning electron microscopy. High resolution and analytical transmission electron microscopy (TEM) and STEM were used to further characterize structure and composition. The growth mechanism was determined to be distinct from the common vapor-liquid-solid (VLS) mechanism in that an elongated crystalline germanide particle was observed at the nanowire tip, rather than a hemispherical Mn particle. Statistical studies of Mn seed particle and resulting nanowire diameters indicate that nanowire nucleation and growth occurs for a small subset of nuclei in a narrow diameter range. Furthermore, the manganese germanide core is always surrounded by an amorphous Mn₃Ge_{1-x} shell of constant width, independent of growth time. Under conditions of continuous TCMn and germane flows, simultaneous axial elongation of the germanide 'leader' and the germanium nanowire occurs with leader growth rates of ~2% of the nanowire growth rate. The simultaneous growth of these nanowire heterostructures was determined to require the diffusion of germanium and manganese adatoms to the leader/nanowire interface where preferential incorporation and elongation occurs. The germanide leader has been identified as Mn₃Ge₃, which is ferromagnetic at room temperature, suggesting that these abrupt heterostructures can act as one-dimensional spin-injectors/spin-filters. Magnetic force microscopy measurements are being undertaken to study the magnetic properties of this phase in the leader.

2:30 PM Student

F4, Synthesis of Epitaxially-Aligned Ge/Si Core-Shell Nanowires: *Irene Goldthorpe*¹; Joshua Ratchford¹; Christopher Chidsey¹; Paul McIntyre¹; ¹Stanford University

Depositing a Si film around a Ge nanowire (NW) creates a structure which may have additional advantageous properties beyond that of a single-element Si or Ge NW. A heteroepitaxially grown shell may allow for engineering of strain in both the shell and the inner core. Moreover, the valence band offset may allow confinement of holes to the core, reducing the influence of surface defects on carrier scattering in p-type NWs. The Ge-core/Si-shell arrangement is desirable for the higher carrier mobilities of Ge and the superior properties of SiO₂ passivation. In this work, vertically aligned arrays of Ge/Si core-shell NWs have been synthesized by CVD. First, <111> Ge NWs were heteroepitaxially grown on Si (111) substrates; the NW diameter was controlled through the use of monodisperse Au nanoparticles as the catalysts. Silane was then used to deposit the shell. The Au remaining on the Ge NW tips is problematic since (i) the Au can catalyze unwanted Si NW growth and (ii) the Au particles at the NW tips diffuse into the structure at the temperatures required to obtain single crystalline Si shells. We have found that Ge NWs dissolve in commercially available wet chemical Au etchants. We have investigated a KI/I₃-based wet etching procedure for Au removal from Ge NWs that does not significantly etch the Ge so that a heteroepitaxial Si shell can subsequently be deposited. In this presentation, we will discuss a systematic study of Au etching and Si shell deposition process conditions

and their effects on the crystalline quality of the Si shell, as determined by transmission electron microscopy and x-ray diffraction analysis.

2:50 PM Student

F5, Size Effects in the Vapor-Liquid-Solid Growth of Si, Si_{1-x}Ge_x and Si/Si_{1-x}Ge_x Heterostructure Nanowires: *Pramod Nimmatoori*¹; Lew Kok-Keong²; Trevor Clark¹; Xi Zhang¹; Elizabeth Dickey¹; Joan Redwing¹; ¹Pennsylvania State University; ²Naval Research Laboratory

Si and Si_{1-x}Ge_x nanowires (NWs) fabricated by the vapor-liquid-solid (VLS) growth process are promising for potential applications in nanoscale electronics and sensing. However, realization of these applications requires a comprehensive understanding of the VLS growth process. Prior studies have reported a reduction in the growth rate of SiNWs with decreasing wire diameter but size-related growth phenomena relevant to the growth of Si_{1-x}Ge_x alloy nanowires and Si_{1-x}Ge_x/Si axial heterostructured nanowires have not yet been investigated. In this study, VLS growth was carried out in a low-pressure chemical vapor deposition system using SiH₄ and GeH₄ as the precursor gases and H₂ as the carrier gas. Initial studies focused on the effect of Au nanoparticle size on SiNW growth rate. The SiNWs were fabricated using 10 nm and 50 nm Au nanoparticle catalysts dispersed on a polymer-modified sapphire substrate. The growth rate had an exponential dependence on temperature at a constant SiH₄ partial pressure of 5 Torr over a temperature range of 450-525°C. It was found that the activation energy was larger for smaller diameter wires, which suggests that the Gibbs-Thomson effect plays an integral role in SiNW growth at small length scales. The Si_{1-x}Ge_x alloy nanowires, with diameters between 10 and 120 nm, were grown on Au-coated oxidized silicon substrates and Au-impregnated anodized alumina membranes, over a temperature range of 325°C to 500°C and a total pressure of 13 Torr. The SiH₄ and GeH₄ partial pressures were between 0.52-0.65 Torr and 0.0065-0.13 Torr respectively. Chemical compositions of the Si_{1-x}Ge_x wires were determined via X-ray energy dispersive spectroscopy (EDS) in transmission electron microscope (TEM). The Ge concentration was found to increase with the wire diameter, the effect being more prominent below 50 nm. This might be due to variation in Ge solubility in the liquid catalyst with change in size. Si/Si_{1-x}Ge_x heterostructure nanowires, grown at a constant temperature of 500°C, consisted of an initial 12 μm Si segment followed by alternating segments of Si and Si_{1-x}Ge_x grown for 18 seconds each. The SiH₄ and GeH₄ partial pressure was held constant at 0.59 Torr and 0.024 Torr respectively. The composition profiles of the heterostructures were obtained via intensity profiles from high-angle annular dark-field STEM images. The intensity profiles reveal a decrease in interfacial width of both the leading and trailing edges with a decrease in diameter from 15 to 60 nm. The interfacial abruptness of both edges sharpens with decreasing catalyst particle diameter as a result of the reduced time that it takes to saturate and deplete the liquid catalyst of excess Ge. These results show that size-related effects arising from the VLS growth process play a dominant role in the Ge content and interface control of Si_{1-x}Ge_x alloy and heterostructure nanowires.

3:10 PM Break

3:30 PM Student

F6, Nano-Imprint Lithography for Nanowire Fabrication: Doreen Ahmad¹; Sagnik Dey¹; Marylene Palard¹; *Fahmida Ferdousi*¹; Emanuel Tutuc¹; Sanjay Banerjee¹; ¹University of Texas at Austin

Nanowire fabrication has emerged as one of the hottest topics in semiconductor research area these days. Researchers are investigating different smart techniques for successful fabrication of different nanostructures. Among the two approaches (top-down and bottom-up) of nanowire fabrication, bottom-up has drawn much attention. But the issue it has to deal with is most of the precursors (Au etc.) used for it are deep traps in Si. The top-down approach does not require such precursors. E-beam Lithography (EBL) is mostly used for the top-down methodology. But one obstacle for it is that e-beam exposures can be very time consuming for such nano patterning. Nano-Imprint Lithography (NIL) is one of the emergent techniques that can be used for such patterning of nanostructures. The concept of the NIL technique, using the IMPRIO100 from Molecular Imprints Inc., is based on a low viscosity fluid that fills in the cavities of a mold (a 1:1 quartz template with features written with EBL and dry etched in a Reactive Ion Etching reactor (RIE)). The fluid is first dispensed on the substrate wafer and

then the template is brought in contact with the wafer. After UV cure, the fluid becomes a polymer and the template features are transferred onto the wafer by a set of etching process steps. The written pattern on the template covers a size of maximum 25mm×25mm (For our purpose we have used a 10mm×10mm mesa). This mesa pattern is repeatedly imprinted on the same wafer (step, flash and repeat technique) as many times as desired in a reasonable amount of time. This helps us to avoid the long exposures needed by e-beam lithography. For nanowire fabrication, with NIL and subsequent etching steps, we have created nano holes on a Si substrate coated with a SiO₂ (~1000Å) layer. These holes were first patterned on our quartz template and then transferred to the oxide layer. The holes can be filled with our desired material (SiGe used for our purpose) to get the nanowires. This mainly involves an epitaxial CVD growth technique on the wafer with the imprinted and etched holes on the oxide. Finally, the layer (oxide) containing the holes can be selectively etched off leaving the grown vertical nanowires on the substrate. This technique can be used repeatedly to get vertical nanowires of any dimension. Scalability of the nanowire dimensions is mainly limited by our e-beam patterning capability. With templates fabricated these days, up to sub-50nm diameter holes can be e-beam patterned on a template. This gives us great flexibility in engineering the diameter of the holes and replicating them on our substrates to achieve nanowires of desired nano dimensions.

3:50 PM

F7, Late News

4:10 PM Student

F8, Does the Catalyst Influence Minority Carrier Diffusion in VLS-Grown Silicon Nanowires?: *Jonathan Allen*¹; Daniel Perea¹; Eric Hemesath¹; Lincoln Lauhon¹; ¹Northwestern University

The vapor-liquid-solid (VLS) process is used extensively to grow semiconductor nanowires due to the high degree control provided over morphology and composition. It has been shown that the majority carrier type can be controlled by impurity doping, but many questions remain concerning the origins of the electrical behavior of devices. In particular, the influence of surface states and the potential influence of unintentionally incorporated metal catalyst atoms are not well explored. Furthermore, techniques to measure doping levels and minority carrier characteristics in individual nanowires have only recently been described. Here we report quantitative measurement of minority carrier diffusion lengths in semiconductor nanowires using an electron beam induced current (EBIC) technique. These measurements, combined with compositional studies conducted using local electrode atom probe (LEAP) tomography, are used to address the question of whether catalyst incorporation influences minority carrier diffusion in VLS-grown silicon nanowires. Two-terminal Schottky diode devices were fabricated from Au catalyzed VLS-grown n-type Si nanowires. For EBIC measurements, devices were scanned with an electron beam to generate excess carriers in a nanoscale volume, and the excess current was monitored as a function of beam position. In Schottky diode devices under reverse bias, the current was localized near the Schottky contact and decayed exponentially along the device channel with characteristic decay constant, L, the minority carrier diffusion length. Diffusion lengths ranged from 20-80 nm, increasing monotonically with wire diameter and showing no dependence on doping concentration. For comparison, minority carrier diffusion lengths of bulk silicon at comparable doping levels may be greater than 1 μm. The diminished diffusion length in the nanowires can be attributed to a reduction of the minority carrier lifetime resulting from surface recombination. Modeling of the effective carrier lifetime versus nanowire diameter indicated that the diameter dependence of the diffusion length is consistent with a constant surface recombination velocity of ~3x10⁵ cm/s. This value is reasonable for an unpassivated n-Si surface with a native oxide layer and a surface state density of 1.5 x 10¹³ cm⁻². It is often speculated that gold atoms from the catalyst particle may influence the electronic properties of nanowires grown by the VLS method. Gold is an efficient recombination center in Si and therefore is expected to reduce carrier lifetimes. Atomic-scale compositional analysis of single nanowires using LEAP tomography was used to place an upper-bound on the concentration of gold in the nanowire of ~10¹⁷ cm⁻³. In bulk n-Si, expected minority carrier lifetimes due to gold incorporation at this level are almost two orders of magnitude higher than the values we have seen. This suggests that for unpassivated n-Si wires, gold does not play a

dominant role in minority carrier transport.

4:30 PM Student

F9, Using Real Time Microscopy to Quantitatively Determine Nucleation Mechanisms and Kinetics during the Growth of Si Nanowires on Si₃N₄ Substrates: *Bong Joong Kim*¹; Eric Stach¹; Suneel Kodambaka²; Jerry Tersoff²; Mark Reuter²; Kathy Reuter²; Frances Ross²; ¹Purdue University; ²IBM T.J. Watson Research Center

A comprehensive understanding of vapor-liquid-solid (VLS) nanowire growth mechanisms and kinetics is of considerable importance for structural optimization of nanoscale wires with desired properties. Despite over 40 years of research, little has been reported on nanowire nucleation. Here, we report, for the first time, real time transmission electron microscopy (TEM) measurements of the nucleation kinetics of Au-catalyzed Si nanowires. Our direct observations of Au mediated Si nanowire nucleation span from initial observations of the pure solid Au catalyst to final nanowire nucleation. Our measurements show that the nucleation time is linearly proportional to the diameter of the AuSi alloy drop – contrary to behavior expected from the Gibbs-Thomson effect – and that the nucleation rate linearly increases with disilane pressure. These two observations indicate that the rate limiting step throughout the process is the thermally activated dissociative adsorption of disilane on the catalyst surface. Furthermore, we classify the subsequent nucleus growth process of Si nanowires into three regimes: an initial rapid growth of the nucleus, a subsequent slow growth of the nucleus, followed by axial growth of the nanowires away from the AuSi drop. We show that for the initial growth, the growth rate (dr/dt) is simply proportional to the critical supersaturation required to nucleate the nanowire. Additionally, during the slow growth regime and final nanowire growth, the growth rate is proportional to the ratio between the surface area of the AuSi alloy and the Si nucleus. These observations are in an excellent agreement with a theoretical model we have proposed for nanowire nucleation kinetics. Finally, using this model we can extract the critical supersaturation of Si at which nanowire nucleation occurs, leading to the determination of an effective, kinetically controlled liquidus line in the binary phase diagram. These quantitative measurements yield critical data needed for controlling nanowire nucleation during the fabrication of high performance nano-electronic devices based on these structures.

4:50 PM

F10, Late News

Session G:

Organic Thin Film and Crystalline Transistors

Wednesday PM
June 20, 2007

Room: 129
Location: DeBartolo Hall

Session Chairs: David Gundlach, National Institute of Standards and Technology; William Wong, Palo Alto Research Center

1:30 PM

G1, Microstructure-Performance Correlation for Solution Processed Small Molecule TFTs: *David Gundlach*¹; James Royer¹; Behrang Hamadani¹; Oleg Kirillov¹; Wenyong Wang¹; Curt Richter¹; Lee Richter¹; Lucile Teague¹; Sankar Subramanian²; John Anthony²; Sungkyu Park³; Thomas Jackson³; ¹National Institute of Standards and Technology; ²University of Kentucky; ³Pennsylvania State University

We report on a correlation between the electrical characteristics and microstructure for solution processed di-flouro 5,11-bis(triethylsilyl ethynyl) anthradithiophene (diF-TEs-ADT) thin film transistors (TFTs). It was found that the electrical characteristics, mobility, square-law behavior, and subthreshold region characteristics, can be improved significantly by tailoring the interface between the source/drain contacts and the silicon dioxide gate insulator to promote improved film microstructure in the channel region of the device. TFTs were fabricated on heavily doped silicon wafers. A 200 nm thick silicon dioxide film was grown and provided the high quality gate dielectric. Gold source and drain contacts (with a thin titanium adhesion

layer) were deposited by evaporation and defined by photolithography and a lift-off process. Thin films were formed on the substrates by spin coating in room air from a 2% by wt. solution of diF TES-ADT in toluene. The cast films received no post-bake or solvent vapor exposure to modify the microstructure. Heating the solution and/or treating the gold source and drain contacts with pentafluorobenzene thiol was found to greatly influence the microstructure at the contacts. In the best case, large, ordered regions extended approximately 20 micrometers into the channel from each contact. Significant improvement in device performance resulted for TFTs with channel length (L) less than 50 micrometers and a field-effect mobility greater than $0.2 \text{ cm}^2/\text{V}\cdot\text{s}$ was extracted for such TFTs. Low-temperature current-voltage characteristics correlate well with the microstructure and a different temperature-activated mobility is observed for shorter channel devices than for long channel length devices which have less ordered regions in the center of the transistor channel. Di-Bromo and monofluoro substituted TES-ADTs were also investigated and the results from TFTs fabricated using these materials will be contrasted with our findings for diF TES-ADT TFTs.

1:50 PM Student

G2, Ordered and Microstructured Thin Films in Spin Cast F-TES-ADT OTFTs: *Sungkyu Park*¹; John Anthony²; Snaker Subramanian²; Devin Mouery¹; Thomas Jackson¹; ¹Pennsylvania State University; ²University of Kentucky

Key requirements for organic electronics include low-cost processing and high performance devices. Solution-processed organic thin film transistors (OTFTs) are of particular interest due to their potential for low-cost manufacturing.^{1,2} Recently, high mobility spin cast OTFTs were reported using liquid crystalline thiophene polymers. These OTFTs show mobilities as high as $0.7 \text{ cm}^2/\text{V}\cdot\text{s}$ after high temperature annealing ($\sim 248^\circ\text{C}$).¹ In this work we have studied solution-processed OTFTs using the small molecule organic semiconductor fluorinated 5,11-bis(triethylsilylethynyl) anthradithiophene (F-TES-ADT). F-TES-ADT was spin or drop cast to form organic thin film transistors (OTFTs) with carrier mobilities as high as $0.8 \text{ cm}^2/\text{V}\cdot\text{s}$ and $3.5 \text{ cm}^2/\text{V}\cdot\text{s}$, respectively. The high-mobility F-TES ADT films were deposited at room temperature from toluene or chlorobenzene solutions with no annealing steps. The addition of fluorine (F) to the TES-ADT backbone makes the thiophene rings more electron deficient and encourages overlap with the relatively electron-rich middle of the molecule leading to a decrease in intermolecular spacing. In this work, bottom contact OTFTs were fabricated with photolithographically defined source and drain electrodes. A 230 nm thick layer of silicon dioxide was thermally grown on heavily doped (0.015 $\Omega\cdot\text{cm}$) n-type silicon wafers as the gate dielectric. Au source and drain electrodes were deposited by thermal evaporation and patterned using lift-off. To improve metal/organic contact and device performance, a self-assembled monolayer of pentafluorobenzenethiol (PFBT) was deposited from solution onto the Au source/drain electrodes. Drop cast films of F-TES-ADT show molecular terraces and strong x-ray peaks as has been previously observed for similar solution processed organic semiconductors.² For F-TES-ADT, ordered and microstructured film growth was also observed for spin cast films on samples with PFBT treated gold electrodes. For these samples, film growth is more ordered on PFBT-Au surfaces and for samples with patterned PFBT-Au structures, film grains appear to grow out from the PFBT-Au areas into oxide areas. This results in a substantial variation in field effect mobility with gate length as grains growing from the source and drain electrodes meet and overlap. OTFTs fabricated with Au electrodes without PFBT treatment have less ordering, do not exhibit the electrode-related grain microstructure, and typically have mobility less than $0.1 \text{ cm}^2/\text{V}\cdot\text{s}$. Films deposited on PFBT-treated samples have mobilities of $0.1 \sim 0.35 \text{ cm}^2/\text{V}\cdot\text{s}$ from toluene solution and $0.2 \sim 0.8 \text{ cm}^2/\text{V}\cdot\text{s}$ from chlorobenzene solution. ¹I. McCulloch, et al, *Nature Materials*, 5, 328 (2006). ²S. K. Park, C.-C. Kuo, J. E. Anthony, and T. N. Jackson, 2005 IEDM Tech. Digest, 113 (2005).

2:10 PM Student

G3, Charge Transport Measurements on Anisotropic Polythiophene Thin Films Fabricated via Directional Crystallization: *Leslie Jimison*¹; Alberto Salleo¹; ¹Stanford University

Recently, there has been considerable interest in the development of semiconducting polymers for use in printable electronic devices, such as transistors for display backplanes. These materials offer a cost effective

alternative to conventional semiconductors, with key advantages of organic materials being their low processing temperature and possibility of solution processing in ambient, leading to roll-to-roll printing. Performance over recent years has improved, but charge transport in these materials is not yet fully understood. These conjugated polymers generally form a semicrystalline microstructure, consisting of lamellar crystalline regions separated by amorphous grain boundaries. A mobility edge model has been proposed that suggests charge delocalization in the crystallite regions where mobile states exist, with the effective mobility limited by the localized states within the disordered grain boundaries and at defects. We have used a means of controlling the orientation and size of crystallites in the plane of the substrate to explore the relationship between trap density within grain boundaries and charge transport. Regioregular poly-3-hexylthiophene (P3HT) and poly(2,5-bis-alkylthiophen-2-yl)thieno[3,2-b]thiophene (PBTBT) are the materials under investigation. In both cases we have fabricated anisotropic films on glass and silicon substrates with the help of the anisotropic growth of 1,3,5-trichlorobenzene (TCB). We use TCB first as a solvent at an elevated temperature and then as a nucleating agent and substrate for epitaxy once cooled. When TCB is removed from the P3HT/TCB film, an oriented single-component polymer film is left behind, consisting of large (mm^2) domains where the film extinguishes uniformly under crossed polarizers. This suggests long range orientation of the polymer chain axis. Characterization with an AFM reveals crystalline lamellar stacked along the fiber direction separated by amorphous zones – the repeat distance of the lamellar and amorphous zone is approximately 50 nm and the lamellar width is approximately 100 nm. Films were further characterized at the Stanford Synchrotron Radiation facility. This diffraction data confirms the crystalline nature of the films, as well as film anisotropy with respect to chain orientation. Charge transport in the directionally crystallized films was probed by measuring in plane mobilities. Both bottom contact and top contact thin film transistors were made with n-doped silicon substrate serving as the common gate electrode. A 200 nm thermal oxide treated with octadecyltrichlorosilane (OTS) was used as the gate dielectric. Devices were made with different relative orientations between the channel and the polymer film. Transport measurements as a function of charge density and temperature for different orientations of the anisotropic film were used to explore the effect of microstructure on trap distribution.

2:30 PM

G4, Nanoscale Measurements of Density of States and Einstein Relation in Molecular Thin Film Transistors: *Yossi Rosenwaks*¹; I. Epstein¹; O. Tal¹; O. Baboor¹; A. Kahn²; C. K. Chan²; N. Tessler²; ¹Tel-Aviv University; ²Princeton University; ³Technion

The field of organic semiconductors is developing very fast, mainly due to applications in optoelectronics and mechanically flexible inexpensive electronics; however, the physical properties of molecular thin films are relatively ambiguous. In this talk we describe Kelvin probe force microscopy (KPFM) measurements of organic thin film transistors that enabled us to extract the hole density of states, and the generalized Einstein relation (ER) in doped and undoped organic thin films. The measurement is performed by applying a voltage to a bottom gate of a transistor structure while measuring the shift in the highest occupied molecular orbital (HOMO) with the KPFM due to hole injection. The density of states (DOS) is then extracted from the relation between the accumulated injected channel charge and the shift of the molecular levels. The measurements were conducted on a thin film (10nm) of alpha-NPD evaporated in an ultra-high vacuum chamber. Doped alpha-NPD films were formed by co-evaporation of tetrafluoro-tetracyanoquinodimethane (F4-TCNQ) with the host molecules. The DOS of the undoped organic film is a Gaussian with an exponential-like tail and an additional peak at specific physical locations on the film that correspond to interfaces between regions with different surface potential. The doping broadens the DOS and induces several discrete peaks on the main distribution. DOS distributions measured at different lateral positions on the doped samples have similar shape and peak energies, but different peak heights. The ER (the relation between the holes diffusion coefficient and their mobility) is extracted from the DOS measurements and we confirm, experimentally for the first time, the theoretical prediction that the ER in molecular films is larger than its classical value of 1 for almost all practical carrier concentrations. The results are analyzed in the context of several different theoretical approaches of hopping transport in disordered materials.

2:50 PM

G5, Late News

3:10 PM Break

3:30 PM

G6, Frequency Response and Transient Phenomena of Pentacene Thin Film Transistors: *Tetsuhiko Miyadera*¹; Takeo Minari¹; Yoshio Kanamori²; Hiromi Ito¹; Kazuhito Tsukagoshi¹; Susumu Ikeda²; Koichiro Saiki²; Yoshinobu Aoyagi¹; ¹RIKEN; ²University Tokyo

Dynamic characteristics measurement of organic thin film transistors (OTFTs) is one of important topics from both standpoints of fundamental physics and device application, although there have been few works on this subject (T. Miyadera, et al., Appl. Phys. Lett. 89, (2006) 172117.). Accordingly, we have investigated frequency response and transient phenomena of pentacene TFTs and analyzed quantitatively by means of a CR equivalent circuit model, where the effect of trap density, charge injection, and grain boundaries was discussed. Top contact pentacene TFTs were fabricated on Si/SiO₂ substrates. For a direct comparison between DC and AC characteristics, DC device and AC device were simultaneously fabricated on a chip. The chip contains the devices for the analysis of transmission line model (TLM), metal insulator semiconductor (MIS) diode, frequency response, and transient phenomena. In the results of TLM and MIS analysis, we investigated interface effect between metal electrodes (Au) and pentacene thin films. The charge transfer molecule of F₄TCNQ was inserted between Au and pentacene. The effect of local doping was observed both for DC and AC characteristics. The device operation frequency or cutoff frequency was estimated from frequency response analysis. Maximum cutoff frequency of 200 kHz was obtained in the device with 100 μm channel length. Distributed constant circuit model well agreed with the experimental results and the effect of interfaces was discussed from the model. These analyses make it possible to investigate the effect of contact and channel independently and relationship between DC and AC characteristics was revealed. Transient phenomena caused by step gate voltage were investigated at various temperatures from 300 K to 100 K. The results were in good agreement with stretched exponential function ($I = I_0 \exp\{- (t/t_0)^\beta\} + I_0$). This agreement could originate from charge induced trap creation in the channel.

3:50 PM Student

G7, Surface Electronic Properties of GaN for Use as a Hole-Injection Contact for Pentacene: *John Uhlrich*¹; Thomas Kuech¹; ¹University of Wisconsin

GaN could make a favorable hole-injection contact to organic materials of high ionization potential due to its deep valence band with respect to the vacuum level. Our previous studies using both ultraviolet and x-ray photoelectron spectroscopies (UPS and XPS) have determined the energy band offset of the pentacene/n-GaN interface. Our results showed that valence band of GaN lies below the highest occupied molecular orbital (HOMO) of pentacene. Further studies of GaN surface treatments were carried out to determine the important factors affecting the surface electronic structure of GaN and the pentacene-GaN electronic structure. Studies were carried out using (0001)-oriented n-GaN and p-GaN which were grown on a sapphire substrates by halide vapor phase epitaxy (HVPE). The n-GaN samples were degreased with organic solvents and then three sets of surface treatments were performed in sequence: a concentrated aq-HCl etch, annealing at 950°C in pure NH₃, and treating in pure HCl gas at 250°C. Samples were then inserted into the vacuum system with minimal exposure to the ambient. Two n-GaN samples were analyzed by XPS and UPS after each of the three treatment steps. The samples were subsequently heated to 540°C in vacuum to desorb some of the surface species, and then analyzed again by XPS and UPS to determine the changes in surface composition and electronic structure. The results indicated that the aq-HCl etch produced the highest initial chlorine coverage on the surface. These samples also showed the lowest level of oxygen contamination after heating in vacuum, indicating that the chlorine atoms are most effective in chemically passivating the surface. The N/Ga ratios on the GaN surfaces generally increased toward unity as a result of the vacuum anneal. This indicates that the surface stoichiometry can be maintained during annealing at the moderate temperatures studied. Electronic shifts showed that the Fermi level moved toward the valence band as a result of the vacuum anneal for n-GaN samples. An additional p-GaN sample was

analyzed in the same way after treating with aq-HCl for comparison and showed the opposite shift, with the Fermi level moving toward the conduction band, upon annealing in vacuum. This Fermi level motion is consistent with the reintroduction of surface states upon annealing.

4:10 PM

G8, Suppression of Short-Channel Effect in Top-Contact Pentacene Thin Film Transistor: *Kazuhito Tsukagoshi*¹; Fumihiro Fujimori¹; Takeo Minari¹; Tetsuhiko Miyadera¹; Tetz Hamano¹; Yoshinobu Aoyagi¹; ¹RIKEN

We have systematically analyzed transistor characteristics of short-channel organic thin film transistors (OTFTs). The short-channel OTFTs were formed by alignment-free method¹ in which metallic electrode can be formed directly on the organic thin film in top-contact (TC) configuration. The organic channel and the electrode can be formed in-situ formation without exposing air by evaporating the channel molecule and the electrode metal. In the device fabrication, we can introduce doping layer into the contact region by changing the evaporation sequence. The contact with various doping configuration revealed current injection mechanism at the contact in the short channel OTFT. Furthermore, we found a critical issue occurred as a short-channel effect of the organic transistor. Based on the analysis of the issues, we eventually could suppress the short-channel effect. The fabrication method of the OTFT requires a prefabricated insulating structure formed by electron beam lithography. The structure has two cavities with undercut edges, and they are connected under a suspended bridge. A surface of the prefabricated structure was covered with a thin poly-para-xylylene (diX-C) to be hydrophobic. Oblique evaporation of organic semiconductor (Pentacene) and normal evaporation of metal electrodes (Au) onto the prefabricated insulating structure are continuously performed in vacuum. The area under the suspended bridge is the channel of the TC-OTFT. The doping molecule (FeCl₃) was evaporated from vertical direction at the evaporation interval of the pentacene. The short-channel TC-OTFT with various channel length (L) from 0.18 μm to 0.41 μm was characterized. Typical field-effect mobility of the short channel OTFT is 0.01-0.3 cm²/Vs. The field-effect mobility decreased when the channel length became shorter than 0.3 μm in the undoped contact OTFT. This mobility degradation originates in an exponential off-current increase with decreasing L below 0.3 μm while on-current is almost constant. The variety of the doping layer embedded in the electrode clearly showed the resistive region for the charge injection from the metal electrode to conduction channel in the TC-OTFT. The drain current flows as the SCLC because the high-electric field was directly applied to the short-channel when the critical high-resistive region was filled by the doping molecule. Further optimization of the gate-insulator thickness and channel thickness completely suppressed the SCLC and well-controlled the short channel transistor. The operation of the short-channel transistor was drastically improved, and saturation behavior and clear on/off current operation were achieved within low bias voltage. Furthermore, the optimized short-channel OTFT shows clear enhancement of the field effect mobility as the channel length becomes shorter, possibly indicating a reduction effect of grain number in series contained in the OTFT channel. ¹K. Tsukagoshi, et al. APL 89, 113507 (2006).

4:30 PM Student

G9, Macroscopic vs. Microscopic Profile Optimization for Printed OLED Devices by Large-Area Wet Micro-Printing: *Hongzheng Jin*¹; James Sturm¹; ¹Princeton University

The patterned wet printing of organic materials, such as for Organic Light-Emitting Diodes (OLEDs), is critical for low-cost manufacturing. However, wet-printing techniques, such as ink-jet printing and Large-Area Wet Micro-Printing (LAMP),¹ usually suffer from non-uniformity in film thickness, which will cause poor device performance, non-uniform luminance, etc. The printed material can be thicker in the line edges (coffee stain effect²) or thicker in the center. The non-uniformity is a result of many factors, including evaporation rate, contact line pinning/de-pinning, surface tension and its gradient, solute distribution, etc. In this work, we identify two different non-uniformity regimes, macroscopic shape and microscopic surface features, and demonstrate different approaches to handle these two problems. For macroscopic effects, two solvents with different evaporation rate and/or surface tension are mixed together and used to prepare the "ink" solution to be printed. This co-solvent approach affects the profile by altering

the spatial distribution of the evaporation rate; by inducing a surface tension gradient; and by inducing additional fluid circulation within the droplet. In a surfactant approach, a small amount of surfactant is added to the "ink" to alter the surface tension and possibly the spatial distribution of evaporation flux. Surfactants are found to be able to greatly flatten the profile of the printed film. Even with an improved macroscopic shape, there may still be a pronounced fine structure in the thickness profile. We show a solvent vapor annealing method at room temperature can then remove such microscopic fine features in the profile of wet-printed films. The absorption of solvent vapor depresses the glass transition temperature so the material can move to reduce surface area at room temperature. The interaction of these methods to improve macroscopic and microscopic features will be described. In this work, poly(9-vinylcarbazole) (PVK) is used as the light-emitting polymer to be printed, and chlorobenzene as the main solvent. Droplets were studied in recessed circular windows, with the top surface made hydrophobic by surface-energy modification with 1H,1H,2H,2H-perfluorooctyl-trichlorosilane to locate the drop. In the co-solvent approach, 1,2-dichlorobenzene is added to the PVK in chlorobenzene solution at different concentrations, with best profile achieved at about 15-20% of dichlorobenzene. In the surfactant approach, Novec Fluorosurfactant FC-4432 (3M), is found effective in flattening the profile at a concentration of ~0.005% (ratio to solvent) while it had no negative effect on device characteristics. Surface roughness can be further reduced by a 2 hour solvent vapor annealing in chlorobenzene vapor under room temperature. The positive effect of both the macroscopic and microscopic methods in smoothing profile is supported by the improved light emission pattern in OLEDs. ¹H. Jin and J.C. Sturm, *Mat. Res. Soc. Symp. Proc.* 871E, I6.27 (2005). ²R.D. Deegan, et al., *Nature*, 389, 827 (1997).

4:50 PM

G10, Electrical Characterization, Standards, and Materials Considerations for Printed Electronics Manufacturing: *Paul Brazis¹; Dale McClure¹; Gabriela Dyrce¹; Jie Zhang¹; ¹Motorola, Inc.*

Printed electronics continue to receive active interest due to their promise of pervasive, all-printed circuitry, including printed RFID, active packaging, flexible displays, and other very low-cost, environmentally-friendly, single-use electronic applications of interest. The move from the research laboratory to the manufacturing floor has been primarily impeded by both insufficient semiconductor field-effect mobility and an economically sensible manufacturing process. Additionally, lack of electrical characterization and materials specification standards have also slowed movement towards building a robust and sustainable supply chain. For manufacturable and commercially competitive printed electronics, higher mobility and solution processability need to be achieved within a framework of a standard, traceable characterization process. This presentation will focus on key attributes required for accurate device and circuit characterization, based on the IEEE 1620™ family of standards. Material selection considerations, such as environmental, health, and cost, are discussed, along with possible alternatives to solution-processable organic semiconductors. An emphasis will be placed on key attributes necessary for compatibility with all-printed electronics manufacturing.

Session H: III-Nitride Growth and Characterization of Optical Devices

Wednesday PM
June 20, 2007

Room: 102
Location: DeBartolo Hall

Session Chairs: Russell Dupuis, Georgia Institute of Technology; Andrew Allerman, Sandia National Laboratories

1:30 PM Student

H1, Nitride Nanorod Arrays for Phosphor-Free White Light Emitting Diodes: *Parijat Deb¹; Hogyoung Kim¹; David Ewoldt¹; Mark Oliver¹; Zhiwen Liang¹; R. Edwin Garcia¹; Eric Stach¹; Timothy Sands¹; ¹Purdue University*
Band structure engineering in coherent planar heterostructures is limited

by the critical thickness for misfit dislocation introduction. In nanorod heterostructures, lateral elastic relaxation has the effect of replacing the critical thickness with a critical radius that can be as much as a factor of eight greater than the critical thickness for a given lattice misfit. In the context of nitride semiconductor heterostructures, the enhanced elastic accommodation of lattice misfit strain is expected to allow the fabrication of nanorod heterostructures grown on GaN that emit light over the entire visible spectrum. Not only does lattice relaxation permit greater InN incorporation (e.g., larger InN-rich quantum dots), but the control of strain by varying nanorod diameter on the same substrate should enable monolithic broad-spectrum white LEDs without the need for phosphor down-conversion. In this talk, our recent progress in applying nanoheteroepitaxy to nitride light emitters is presented. Reactive ion etching through a sacrificial porous anodic alumina mask on a silica template is used to expose a GaN underlayer. Selective growth by OMVPE yields faceted nanorods of diameters from 30-100 nm with prismatic sides and a pyramidal cap. The presence of free surfaces promotes termination of threading dislocations originating from the substrate. Lateral relaxation of the lattice misfit strain allows grading of the InN mole fraction along the nanorod axis, while the additional relaxation about the apex of the pyramidal promotes the growth of InN-rich quantum dots. X-ray diffraction and cathodoluminescence show that the growth conditions that yield an InN mole fraction of 0.09 in a (In,Ga)N film grown on GaN result in an effective InN mole fraction of 0.3 in a nanorod, yielding a CL peak at 520 nm. GaN nanorod p-n junctions have also been fabricated by doping the nanorods with Mg. Arrays of these p-n junction nanorods contacted by a common Pt ohmic contact show rectifying behavior with a forward turn-on voltage of 2 V, reverse breakdown voltage of 20 V and ideality factor of ~11. The remaining challenges - including internal surface passivation, ballistic carrier effects and ohmic contacts - toward the goal of a phosphor-free monolithic white LED will be discussed. The authors acknowledge support from the Department of Energy (award no. DE-FC26-06NT42862) and the National Science Foundation (ECS-0424161).

1:50 PM

H2, High Brightness and High External Efficiency InGaN/GaN Light Emitting Diodes on Semipolar {10-1-1} Bulk GaN Substrates: *Anurag Tyagi¹; Hong Zhong¹; Natalie Fellows¹; Michael Iza¹; James Speck¹; Steven Denbaars¹; Shuji Nakamura¹; ¹University of California, Santa Barbara*

High power and high efficiency semipolar {10-1-1} InGaN/GaN light-emitting diodes (LEDs) have been fabricated on low extended defect density semipolar {10-1-1} bulk GaN substrates by conventional metal organic chemical vapor deposition (MOCVD). The LEDs have a dimension of 300 x 300 μm² and are packaged in an epoxy resin. The output power and external quantum efficiency (EQE) at a driving current of 20 mA were 20.58 mW and 33.91% respectively, with peak electroluminescence (EL) emission wavelength at 411 nm. The LEDs show minimal shift in peak EL wavelength with increasing drive current along with a minimal drop off in EQE at higher drive currents. The EL emission has been confirmed to be partially polarized along the [11-20] direction.

2:10 PM

H3, Characterization of Green LED Using p-InGaN and p-InGaN/p-GaN Superlattices as p-Type Layer: *Jianping Liu¹; Jae Limb¹; Jae-Hyun Ryou¹; Andy Ewing¹; Dongwon Yoo¹; Russell Dupuis¹; ¹Georgia Institute of Technology*

High-efficiency "true" green LEDs (emitting at ~550nm) are one of the key elements in realizing high-brightness RGB-based white-lighting systems. LEDs emitting at true green wavelengths have suffered from a low internal quantum efficiency (IQE) compared to blue (InGaN) and red (InAlGaP) LEDs. This deficiency in green LEDs is believed to be related to reduced materials quality and fundamental physical properties of the active region. Because the InGaN quantum-well active region of green LEDs contains a high indium alloy composition and a corresponding large lattice mismatch, it has a reduced material quality and contains huge piezoelectric fields induced by the large strain. The piezoelectric field reduces the overlap of the electron-hole wave functions, and so results in reduced IQE in green LEDs. In addition, other effects can strongly impact InGaN materials with high indium content, e.g., detrimental annealing of the MQW active region during the subsequent growth of the p-type contact layers. In this study, the

optical and structural characteristics of green LEDs employing p-InGaN and p-InGaN/p-GaN superlattices (SLs) were presented. For the green LED structures, the growth conditions of each layer, especially the p-type layer and the active layer, were calibrated to improve LED performance. Van der Pauw-geometry Hall-effect measurements revealed a 300K free-hole concentration of $p \sim 1.6 \times 10^{18} \text{ cm}^{-3}$, mobility of $\mu \sim 7 \text{ cm}^2/\text{V}\cdot\text{s}$ for p-In_{0.04}Ga_{0.96}N; Mg layers grown at 840°C in a nitrogen ambient, while a hole concentration of $p \sim 5 \times 10^{17} \text{ cm}^{-3}$, mobility of $\mu \sim 7 \text{ cm}^2/\text{V}\cdot\text{s}$ for p-GaN:Mg layer grown at 930°C in a hydrogen ambient. We have shown previously that improved EL intensity can be obtained by employing such p-InGaN layers in place of p-GaN:Mg layers, which was attributed to higher hole concentration and less thermal damage to the active region. For the LEDs with p-In_{0.04}Ga_{0.96}N:Mg layer grown at 840°C, only a slight decrease in PL intensity was observed compared to similar structures grown without a p-layer. However, pits are observed for p-In_{0.04}Ga_{0.96}N:Mg layers, which may be the path way for reverse current leakage. In order to decrease the reverse current leakage, p-In_{0.04}Ga_{0.96}N/p-GaN SLs were developed. The hole concentration of p-In_{0.04}Ga_{0.96}N/p-GaN SLs is close to that of p-In_{0.04}Ga_{0.96}N, and is much higher than that of p-GaN grown at an acceptably low temperature. In addition, pits disappear in p-In_{0.04}Ga_{0.96}N/p-GaN SLs. In order to study the structural and optical characteristics of green LEDs with p-InGaN and p-In_{0.04}Ga_{0.96}N/p-GaN SLs layers, I-V characterization and EL measurements were performed and the results will be described in detail.

2:30 PM

H4, Junction Temperature Analysis of GaInN/GaN Multi-Quantum Well Light Emitting Diodes by Micro-Raman Spectroscopy: *Jayantha Senaviratne*¹; Yufeng Li¹; Mingwei Zhu¹; Yong Xia¹; Wei Zhao¹; Theerdatch Detchprohm¹; Christian Wetzel¹; ¹Future Chips Constellation and Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute

The junction temperature of light emitting diodes (LEDs) is one of the most critical parameters that affect conversion efficiency, output power, and life time of LEDs. Joule losses in the device are the origin of the self-heating. In order to further optimize GaN-based LEDs to higher efficiency, an accurate measurement of the actual temperature and its distribution across the device die is necessary. Recently, a convenient method to determine the junction temperature has been proposed by comparing the forward voltage under ambient temperature with that under device operation.² On the other hand, micro-Raman spectroscopy¹ allows measurements with a high spatial resolution across the die. In this study, we present junction temperature of GaN based LEDs grown on sapphire and GaN substrates using micro-Raman spectroscopy. LED device structures consist of five GaInN/GaN multi-quantum wells sandwiched between n-type GaN on sapphire or GaN and p-type GaN layer grown by metal organic vapor phase epitaxy (MOVPE). Temperature measurements were performed by using micro-Raman technique at backscattering configuration with excitation energy of 785 nm. Junction temperatures were deduced by considering the temperature dependent Raman peak shift of prominent GaN E2(high). Temperature dependent Raman peak position of GaN was calculated using the empirical formula for temperature dependent Raman peak position of GaN given by Liu et al.³ Temperature measurements were performed at drive currents at 150 mA and beyond. Results reveal that the junction temperature of LEDs grown on sapphire is significantly higher than that of the LEDs grown on bulk GaN substrate. This can be explained by the low thermal conductivity of sapphire substrate which acts as a thermal barrier leading to trap larger amount of heat in the device in comparison to the LED grown on higher thermal conducting GaN substrate. In parallel, a current-dependent electroluminescence (EL) study reveals that for lower injection current the EL peak wavelength shifts to the blue while for the high injection current the EL peak wavelength shifts to the red. We explain this phenomenon by considering the competition between blue and red shifts originated by quantum confined Stark effect and temperature increment, respectively. Acknowledgements: This work was supported by a DOE/NETL Solid-State Lighting Contract of Directed Research under DE-FC26-06NT42860. ¹Y. Xi and E. F. Schubert, Appl. Phys. Lett. 85, 2163 (2004). ²M. Kuball, J. W. Pomeroy, S. Rajasingham, A. Sarua, M. J. Uren, T. Martin, A. Lell, and V. Harle, Phys. Stat. Sol. (a) 202, No. 5, 824 (2005). ³M. S. Liu, L. A. Bursill, S. Praver, K. W. Nugent, Y. Z. Tong, and G. Y. Zhang, Appl. Phys. Lett. 74, 3125 (1999).

2:50 PM Student

H5, Growth and Characterization of Al_xGa_{1-x}N Ultraviolet Avalanche Photodiodes on GaN Substrates: *Dongwon Yoo*¹; Jae Limb¹; Jae-Hyun Ryou¹; Shyh-Chiang Shen¹; Andy Ewing¹; Yair Korenblit¹; Drew Hanser²; Edward Preble²; Keith Evans²; Russell Dupuis¹; ¹Georgia Institute of Technology; ²Kyma Technologies, Inc.

Wide-bandgap GaN-based avalanche photodetectors (APDs), such as AlGaN *p-i-n* diodes, are excellent candidates for short-wavelength photodetection due to the capability of operating in the solar-blind UV spectral region, $\lambda < 290 \text{ nm}$. For the growth of GaN-based heteroepitaxial layers on lattice-mismatched substrates such as sapphire and SiC, a high density of defects is introduced, thereby causing device failure by premature microplasma breakdown before the electric field reaches the level of the bulk avalanche breakdown field, which has hampered the development of Group III-nitride based APDs. We have demonstrated GaN *p-i-n* APDs with record-high gains grown on free-standing GaN substrates. In order to achieve intrinsically solar-blind APDs, the use of wider-bandgap material than GaN is required; but the growth of AlGaN APD structures on GaN substrates introduces technological challenges such as less perfect materials quality due to dislocations and strain and even strain-induced cracking, as well as a limitation in doping, etc. In this study, we investigate on the growth and characterization of the AlGaN-based APDs on GaN substrates. Epitaxial layers of AlGaN *p-i-n* ultraviolet avalanche photodiodes on GaN substrates were grown using a Thomas Swan CCS 7x2 close-coupled showerhead MOCVD reactor. Improved crystalline and structural quality for Al_xGa_{1-x}N epitaxial layers were achieved by employing optimum growth parameters on low-dislocation-density bulk GaN substrates in order to minimize the defect density in epitaxially grown materials. For Al_{0.05}Ga_{0.95}N APDs, a compositionally graded layer from unintentionally doped GaN to Al_{0.05}Ga_{0.95}N was inserted as a strain-management layer for the crack-free growth. The epitaxial layer structure consists of an *n*-type Al_{0.05}Ga_{0.95}N:Si layer, followed by an unintentionally doped Al_{0.05}Ga_{0.95}N drift region (0.25 μm , $n < 5 \times 10^{16} \text{ cm}^{-3}$), a *p*-type AlGaN: Mg⁺ layer, and topped with *p*-type GaN:Mg⁺⁺ (heavily doped) contact layer. The devices were fabricated into 30 μm - and 50 μm -diameter circular mesas. The forward *I-V* characteristics and low reverse-bias voltage (up to -100V) *I-V* characteristics were measured. No microplasmas or side-wall breakdown luminescence was visually observed. The photocurrent was obtained using a UV lamp-monochromator operating at a peak emission wavelength of $\sim 250 \text{ nm}$. The avalanche gain reaches a maximum value of ~ 50 at a voltage of 86.75V. For Al_xGa_{1-x}N APDs with higher Al-content, the crack-free growth of thick Al_xGa_{1-x}N on a bulk GaN substrate has been investigated by employing various strain management layers such as Al_xGa_{1-x}N ($x > 0.5$) interlayers and/or AlN/GaN multiple short-period superlattice structures. Growth of Al_xGa_{1-x}N ($x > 0.1$) PIN structures with higher Al-content and APD device performance of will be reported.

3:10 PM Break

3:30 PM Student

H6, Recombination Dynamics in Ultraviolet Light-Emitting Diodes with Si-Doped Al_xGa_{1-x}N/Al_yGa_{1-y}N Multiple Quantum Well Active Regions: *Kaixuan Chen*¹; Yangang Xi¹; Frank Mont¹; Jongkyu Kim¹; E. Schubert¹; Wayne Liu²; Xiaolu Li²; Joseph Smart²; ¹Rensselaer Polytechnic Institute; ²Crystal IS

Ultraviolet light-emitting diodes (UV LEDs) with Al_xGa_{1-x}N/Al_yGa_{1-y}N multiple quantum well (MQW) active regions, doped in the barriers with different Si doping levels, show a sharp near-bandedge emission line (UV luminescence). Some samples have a broad sub-bandgap emission band centered at about 500 nm (green luminescence) in addition to the near-bandedge emission. The electroluminescence (EL) intensities of the UV and green emission line are studied as a function of the injection current. For the sample grown on the AlN substrate under optimized growth conditions, the UV luminescence intensity increases linearly with the injection current, following a power law with an exponent of 1.0, while the green luminescence intensity increases sub-linearly with the injection current. On the contrary, the samples grown on the sapphire substrate show a superlinear (to the power of 2.0) and linear (to the power of 1.0) dependence on the injection current for the UV and green luminescence, respectively. A theoretical model is proposed to explain the relationship between the luminescence intensities

and the injection current. The results obtained from the model are in excellent agreement with the experimental results. The model provides a method to evaluate the dominant recombination process by measuring the exponent of the power-law dependence.

3:50 PM

H7, Radiative and Non-Radiative Lifetime Studies of Enhanced UV Emission Mechanisms in AlGaIn Containing Nanoscale Compositional Inhomogeneities: *Gregory Garrett¹; Anand Sampath¹; Hongen Shen¹; Michael Wraback¹; ¹U.S. Army Research Laboratory*

The radiative efficiency of ultraviolet emitters can be improved through a combination of reduced radiative lifetime and enhanced nonradiative lifetime. Internal quantum efficiency (IQE) in conventional nitride semiconductor UV LEDs has traditionally been low due to a large density of defects acting as nonradiative centers associated with growth on lattice-mismatched substrates such as sapphire. Recently, we have demonstrated that AlGaIn alloys containing nanoscale compositional inhomogeneities (NCI) grown by plasma-assisted molecular beam epitaxy can have enhanced IQE as high as 30%. In this paper, we measure radiative and nonradiative lifetimes and correlate them with NCI density in these alloys to determine the underlying mechanism of enhanced radiative efficiency. We focus on two NCI epilayers of particularly high absolute room-temperature photoluminescence (PL) brightness. Low temperature PL shows that the NCI emission peak is red-shifted from band edge (BE) by 300 meV in Sample A (~33% AlN with a 225 nm thick NCI epilayer) and 261 meV in Sample B (~28% AlN with a 495 nm thick NCI epilayer), both much larger than that traditionally seen and associated with band tail states. Although room-temperature PL of Sample A and Sample B are qualitatively of equal intensity, Sample B is significantly brighter at low temperature, when nonradiative recombination is suppressed, implying a larger density of NCI, but a concomitant lower IQE (15% vs. 25%), as obtained from temperature dependent integrated PL intensities. Time-resolved PL measurements were used in conjunction with IQE to determine radiative and nonradiative lifetime. In both samples the BE data exhibit a decreasing lifetime with increasing temperature, consistent with the freeze out of non-radiative states in the BE matrix at low temperature, while the NCI emission shows a relatively constant lifetime. The relative temperature independence of the NCI radiative lifetime supports the idea of a lower dimensionality of the NCI, and the shorter radiative lifetime relative to the BE is consistent with enhanced emission. Moreover, in both samples the smaller NCI density of states and rapid transfer of carriers from the matrix to the NCI produce a high carrier concentration in the NCI that saturates nonradiative sites while reducing radiative lifetime relative to the BE. Sample B, however, possesses a longer radiative lifetime and a shorter nonradiative lifetime at room temperature than Sample A, most likely due to the larger density of NCI states in Sample B, leading to a smaller carrier concentration in the NCI. This combination of saturation of nonradiative recombination sites through carrier transfer from the matrix and concentration in the NCI and concomitant lower radiative lifetimes of the NCI relative to the matrix, associated with the higher concentration in and possibly lower dimensionality of the NCI, provides an attractive option for development of high efficiency UV LEDs.

4:10 PM Student

H8, Spectroscopic Cathodoluminescence of V-Defects in GaInN/GaN Quantum Wells: *Yong Xia¹; Theeradetch Detchprohm¹; Jayantha Senawiratne¹; Yufeng Li¹; Wei Zhao¹; Mingwei Zhu¹; Christian Wetzel¹; Daniel Koleske²; Mary Crawford²; Stephen Lee²; Katherine Bogart²; ¹Rensselaer Polytechnic Institute; ²Sandia National Laboratories*

With the improvement of growth techniques, GaN and its related alloys of GaInN and AlGaIn are the most advanced material for fabricating green, blue and UV light emitting diodes (LEDs) and laser diodes. However, high densities of threading dislocations (TDs) in the active light emitting regions have been shown to reduce device performance, particularly in the green spectral range. One common explanation is that TDs act as non-radiative recombination centers in the GaInN/GaN quantum wells (QWs). In an attempt to identify the connection between TDs and non-radiative recombination, we analyzed QW samples with significantly different luminescence performance. The structural difference is a 300 nm GaInN underlayer (UL) between the n-GaN and the QW region in one of the samples. This UL induces a high density of very regular V-defects as observed in scanning

electron microscopy (SEM). These V-defects are known to nucleate on TDs and therefore may impact recombination processes in the vicinity of TDs. From room-temperature large-area cathodoluminescence (CL) spectroscopy, we find that the sample with the UL exhibits 20-fold enhanced luminescence intensity in the blue spectral region over that without the UL. Upon lowering the sample temperature to 8 K, the integrated intensity increases for both samples and can be described by a thermal activation barrier. The sample with an UL remains the better performing one for the entire temperature range. In order to resolve the impact of the V-defects, we performed spectral CL mapping with high spatial resolution and variable temperature (8-297K). In the emission of the UL, we find a close spatial correlation with V-defects seen in SEM. At 8 K in locations free of V-defects this emission peaks at 380 nm, while near the defects it peaks at 383 nm. The variation of UL emission intensity from V-defects and regions free of v-defects is less than 20%. At the wavelength of the QW, where the UL induces the strong overall emission enhancement, we obtain images with only a weak contrast. Compared to the UL emission, neither the QW wavelength nor intensity show as good a correlation with the V-defects. These findings suggest that light extraction via the pyramidal surfaces of the V-defects cannot account for a 20-fold luminescence enhancement seen in this material. Judging from the CL mapping of both the UL and QW emission, V-defects do not appear to significantly reduce radiative recombination. We will discuss the possible impact of our findings on GaInN/GaN LED device performance. This work was supported by a DOE/NETL Solid-State Lighting Contract of Directed Research under DE-FC26-06NT42860. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

4:30 PM Student

H9, Characterization of Homoepitaxial and Heteroepitaxial GaInN/GaN Light Emitting Diodes by Transmission Electron Microscopy: *Mingwei Zhu¹; Yong Xia¹; Wei Zhao¹; Yufeng Li¹; Jayantha Senawiratne¹; Theeradetch Detchprohm¹; Christian Wetzel¹; ¹Rensselaer Polytechnic Institute*

GaN materials have attracted more attentions in recent years for their realization of high efficiency blue and green light emitting diodes (LEDs). However, these devices still suffer from the poor crystal quality of the epitaxial layer, which is mainly caused by high densities of threading dislocations (TDs) ($1E8$ to $1E10$ cm⁻²). It was found that performance of these LEDs could be further improved by reduction the TD density, especially for green LEDs,¹ yet a quantitative comparison would be more helpful to reveal how big its role is. Also the effect of V-defects on the optical property of LEDs still remains controversial, so it is necessary to evaluate samples with different TD densities and/or V-defects. Recently, we demonstrated that the light output power of homoepitaxial LEDs can be more than one order of magnitude higher than that of heteroepitaxial LEDs.² These GaInN/GaN LEDs were grown on c-plane bulk GaN and sapphire substrates by MOVPE, respectively. In order to understand the relationships between microstructures and performance of these LEDs, cross-sectional and plan-view transmission electron microscopy (TEM) were performed. Our results show that the TD density of LEDs grown on GaN bulk is about two orders of magnitude lower than that of LEDs grown on sapphire. Also there are no additional TDs generated from the growth of epitaxial layers for LEDs grown on GaN bulk. At the mean time, large V-defects were observed when edge-type TDs cross the quantum wells (QWs). On the other hand, V-defects were not observed in QW region of LEDs grown on sapphire in spite of the higher TD density. Apparently the generation of V-defects can be suppressed in MOVPE even in the presence of TDs. This gives us direction on how to grow LEDs with V-defects free and low TD density. In order to assess the epitaxial quality more quickly, we employ the etch pit method by chemical etching. After the optimization of etching parameters at various conditions, two distinct types of etch pits were revealed on the GaN surfaces by AFM. The etch pit density counted from AFM shows very good agreement with dislocation density counted from plan-view TEM images. This work was supported by a DOE/NETL Solid-State Lighting Contract of Directed Research under DE-FC26-06NT42860. ¹C. Wetzel, T. Salagaj, T. Detchprohm, P. Li, and J.S. Nelson; Appl. Phys. Lett. 85(6), 866-8 (2004). ²T. Detchprohm, Y. Xia, Y. Xi, M. Zhu, W. Zhao, Y. Li, E.F. Schubert, L. Liu, D. Tsvetkov, D. Hanser, and C. Wetzel; J. Crystal Growth, 298, 272-5 (2007).

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H10, Late News

Session I: Growth and Processing of Nanostructured Materials

Wednesday PM
June 20, 2007

Room: 155
Location: DeBartolo Hall

Session Chairs: Ganesh Balakrishnan, University of New Mexico; Glenn Solomon, National Institute of Standards and Technology

1:30 PM Student

II, Selective GaAs Quantum Dot Array Growth Using Diblock Copolymer Nanopatterning: *Joo Hyung Park*¹; Anish Khandekar¹; Sang-Min Park¹; Luke Mawst¹; Thomas Kuech¹; Paul Nealey¹; ¹University of Wisconsin-Madison

To reach the full theoretical potential advantages of ideal Quantum Dots (QDs) for diode lasers and photodetectors, elimination of the wetting layer, which is inherent to self-assembled QDs of Stranski-Krastnow (SK) growth mode, and achieving a uniform mono-modal QD size distribution is needed. The SK QD approach is complicated by the randomness of the QD size distribution and inherent presence of the wetting layer. These factors have been experimentally identified as the underlying cause for low optical gain and high temperature sensitivity in diode lasers which result from carrier leakage out of the QDs into the wetting layer. An alternate approach to QD formation is the use of nanopatterning with diblock copolymers combined with selective MOCVD growth. We utilize cylinder-forming PS-b-PMMA which have the ability of preserving the hole size through the pattern transfer procedures. The combination of diblock copolymer lithography with selective MOCVD growth of the QDs could lead to a higher degree of control over QD shape, size uniformity, and composition over the self-assembly process. Since the SK self-assembly process is not employed, the problematic wetting layer states are eliminated and improved optical gain can be expected. Control over the QD height, shape, and strain, also allows for the design of increased energy spacing between ground and excited QD states and hence a wider control or selection of the emission wavelengths. Since the QD strain is decoupled from the size, the process also has potential for achieving longer wavelength emission compared with SK QDs. The QD patterning is prepared by dense nanoscale diblock copolymer lithography, which consists of perpendicularly ordered cylindrical domains of polystyrene-block-poly(methylmethacrylate) (PS-b-PMMA) matrix. To transfer polymer patterns to QD arrays, several mask materials have been taken under consideration. Firstly, to characterize the profile and distribution of the QDs, a dielectric template mask was utilized and the polymer patterning is transferred on it. After the pattern transfer to the dielectric and subsequent removal of the polymer, single crystal GaAs QDs are selectively grown by MOCVD. SEM images indicate that the QD density is larger than $5 \times 10^{10}/\text{cm}^2$, comparable to SK growth mode and the size distribution peaks at a 12nm diameter. To grow QDs selectively and subsequently cover the QDs in situ, a nanopatterned $\text{Al}_x\text{Ga}_{1-x}\text{As}$ template mask is also being investigated. After the pattern transfer to a 15nm thick $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($x=0.7$) template layer using RIE, the native oxide on the patterned AlGaAs surface acts as a selective growth mask for InAs QDs. After deposition of the QDs, capping layers can be grown on QDs without removing the sample from the reactor. AFM characterization has been used to study the selective QD growth. We are currently investigating optimal growth conditions for covering the QDs and characterizing the photoluminescence.

1:50 PM

I2, Controlled Nucleation of InAs Quantum Dots Using Focused Ion Beams: *Hugh McKay*¹; Aaron Dehne¹; Paul Rudzinski¹; Joanna Mirecki Millunchick¹; ¹University of Michigan

In this work, the influence of Ga⁺ ion dose on InAs quantum dot formation was studied using a novel grow-pattern-characterize system. An ultra high

vacuum focused ion beam (FIB) column, which is integrated to a molecular beam epitaxy growth system, was used to pattern GaAs layers grown on GaAs(001) substrates. After patterning, samples were transferred to the growth chamber in vacuo, and a thickness $2.0 < h < 2.8$ ML of InAs was deposited at a substrate temperatures of 530°C. FIB patterns consisted of either arrays of individual points or arrays of uniformly dosed $5 \mu\text{m}$ squares. The individual point arrays had ion beam spot times ranging from 4 to 1600 μs while the uniformly dosed squares had ion doses ranging from 10^{12} to 10^{15} ions/cm². After removal from the vacuum system, samples were examined via tapping mode atomic force microscopy. Atomic force micrographs of large scale uniformly dosed areas show an apparent reduction in the quantum dot critical thickness and the area density of the dots is influenced by the ion dose, which is related to ion induced roughening of the surface. Atomic force micrographs of individual point arrays showed precise control of InAs quantum dot nucleation locations was achieved. For an InAs thickness $h=2.0$ ML, quantum dots were found to nucleate only on locations patterned with the FIB, other areas of the sample being virtually devoid of dots. Quantum dot fidelity was observed to increase with increasing FIB spot time. Further increases in spot time led to an increase in the probability of finding multiple quantum dots nucleating around the individual FIB pattern point. For greater thickness of InAs, dots were found to preferentially nucleate on pattern points but a significant dot density between points was also observed. Conditions necessary for 100% fidelity and narrow size distributions for individually nucleated quantum dots will be discussed.

2:10 PM Student

I3, Controlled Growth of Quantum Dots and Nanopillars on Patterned GaAs Substrate by MOCVD: *Ping-Show Wong*¹; Ganesh Balakrishnan¹; Noppadon Nuntawong¹; Jun Tatebayashi¹; Diana Huffaker¹; ¹Center for High Technology Materials, University of New Mexico

We report selective area nano-epitaxy to form both patterned quantum dots (PQDs) and nanopillars. The selective InAs quantum dot (QD) nucleation on nano-faceted GaAs pyramidal facets is explored. This technique of QD growth enables better control of QD shape and size, than is possible with the Stranski-Krastanow (SK) growth mode. The GaAs pyramids are formed by metal-organic chemical vapor deposition (MOCVD) in patterned SiO_2 mask on a (001) GaAs substrate. The patterning is done by interferometric lithography and the circular patterns in SiO_2 are 25 nm deep and 230 nm in diameter, with a pitch of 330 nm. The GaAs pyramids are characterized by well-defined equilibrium crystal shapes (ECS) defined by three crystal plane families including {11n}, {10n} and (001). Subsequent patterned QD (PQD) nucleation on the GaAs pyramidal facets is highly preferential towards the (11n) planes due to superior energy minimization, and the shape of the QDs on the (11n) planes is also highly predictable and uniform. The GaAs ECS pyramid and highly faceted PQDs are examined using high-resolution scanning electron microscopy (HRSEM), and room temperature photoluminescence (PL) and electroluminescence from 1.2 to 1.6 μm has been demonstrated. Three dimensional quantum confinement is confirmed with low temperature (77K) PL. The same lithographically defined patterns are used in the development of GaAs and GaSb nanopillars on GaAs (111)B substrates. The superior uniformity and arbitrary placement of the nanopillars along with easy electrical contacting schemes make these ensembles extremely attractive for nanoscale electronic devices. In this study, the nanopillar growth is conducted under a variety of conditions including III/V rations, substrate temperatures and growth rates. Nanopillars exhibit highly crystallographic hexagonal cross-section formed by (001) and (011) sidewalls. Pillar dimensions are ~ 200 nm in diameter and $> 2 \mu\text{m}$ in length. Micro-PL and electrical properties of these wires are also investigated.

2:30 PM

I4, Formation and Coarsening of Ga Droplets on Focused-Ion Beam Irradiated GaAs Surfaces: *Ben Cardozo*¹; Weifeng Ye¹; John Mansfield¹; Rachel Goldman¹; ¹University of Michigan

The formation of submicron diameter metallic droplets on III-V compound semiconductor surfaces has been observed under a number of conditions in which the surface is group III-rich. In the case of GaAs, Ga droplets have been observed following heating in a vacuum, exposure to a Ga molecular beam in the absence of As, and irradiation with either blanket or focused-ion beams (FIB). In all cases, As is preferentially desorbed or sputtered due to its lower

surface binding energy in comparison with that of Ga. During FIB irradiation of GaAs, both Ga ion implantation and preferential As sputtering contribute to Ga-enrichment of the surface, and subsequent Ga droplet formation. Recently, ordered arrays of Ga droplets have been demonstrated via FIB irradiation of surfaces pre-patterned with FIB-fabricated holes. Although processing conditions for the preferential nucleation of droplets within such holes have been identified, the mechanisms of their formation and coarsening are not well understood. Therefore, we have investigated the effects of several ion beam parameters on the Ga surface concentration, critical dose for droplet formation, and average droplet diameter. In each experiment, 10-30 keV Ga ions were used to pattern the GaAs surface with or without an array of holes. Following patterning, FIB irradiation was performed either continuously, without interruption between 2D scans, or with ~2 minute delays between subsequent 2D scans. In the case of continuous scanning, droplets initially nucleate within the pre-patterned holes. As the dose is increased, these droplets grow while the area between the holes remains pristine. At doses higher than $3 \times 10^{16} \text{ cm}^{-2}$, droplets nucleate and grow between the pre-patterned holes, and droplet ordering is no longer obvious. Continued FIB irradiation leads to a higher density of droplets, apparently limiting the growth of existing droplets within the holes. In the case of delayed scanning, for the lowest doses, droplets are also confined to the holes. With increasing dose, the droplets in the holes continue to grow, without the formation of droplets in the interstices. For doses $> 1.5 \times 10^{16} \text{ cm}^{-2}$, x-ray energy dispersive spectroscopy reveals ion-beam energy dependent surface Ga concentrations. Additionally, the critical dose for Ga droplet nucleation is dependent on the ion beam energy, with higher critical doses for higher ion energies. Together, these findings suggest a droplet formation mechanism which involves Ga precipitation from a Ga-rich surface layer followed by droplet coarsening due to Ga surface diffusion. The Ga precipitation is likely dependent on the concentration of surface defects. The Ga surface diffusion is enhanced (suppressed) by the reduction (increase) in Ga surface flux which occurs with (without) time-delays in ion-beam scanning.

2:50 PM Student

I5, Suppression of Phase Transformation in Organic Encapsulated Germanium Nanoparticles: Suk Jun Kim¹; Carol Handwerker¹; Eric Stach¹; Kevin Grossklau¹; Alexander Wei¹; Ling-Shao Chang¹; ¹Purdue University

The crystal structure and coalescence behavior of butyl-capped crystalline Ge nanoparticles were characterized as a function of particle size and temperature using in-situ transmission electron microscopy (TEM), x-ray diffractometry (XRD), differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). The Ge nanoparticles were synthesized at room temperature in dimethoxyethane by reduction of GeCl₄ with Na(naphthalide) and subsequent reaction with butyl Grignard. The synthesized nanoparticles had an average particle size of approximately 4nm, and remained surrounded by a significant amount of organic residue, despite extensive cleaning. All particles were ST12, a metastable tetragonal phase of bulk Ge which has a direct band gap at 1.47 eV. In the in-situ TEM experiments, nanoparticle coalescence was observed in the temperature range of 200°C to 400°C. As noted before by Chiu, et al. [Langmuir, 2006], a significant number of nanoparticles – with an average size of 5.4nm – formed in the organic residue upon heating to 300°C. Although the particle size increased to over 70nm during coalescence, the particles remained ST12 throughout, even with temperature increases to 500°C.

3:10 PM Break

3:30 PM

I6, Growth and Characterization of GaAs Quantum Dots in Al_{0.3}Ga_{0.7}As Grown by Molecular-Beam Epitaxy: Bingyang Zhang¹; Shinichi Koseki¹; Yoshihisa Yamamoto¹; ¹Stanford University

Using the emission properties of three-dimensional confinement of the quantum dots(QD), we can realize a variety of optoelectronic device structures for physics and engineering including low-threshold lasers and a single-photon sources, for applications ranging from high-efficiency communications to emerging area in quantum key distribution and quantum information processing. Typically, InAs-based QDs are used, created via the 7% lattice mismatch. This leads to QDs of approximately 30 nm in diameter. Since, the oscillator strength of the dipole QD emission dipole, and hence the brightness from the emission, scales with the QD size and Bohr radius, so it

desirable to increase the QD size. One avenue employed uses InGaAs QDs. Here, we demonstrate an alternative approach to obtain bright-emission using GaAs QDs in Al_{0.3}Ga_{0.7}As. Due to the very small lattice mismatch between GaAs and Al_{0.3}Ga_{0.7}As layers, a new crystal growth technique is necessary. In this talk, we study GaAs/Al_{0.3}Ga_{0.7}As QDs grown with a very low growth temperature (~300°C) using the Ga droplet epitaxy method. A variety of growth parameters are investigated, including the effects of growth temperature, deposition rate, thickness and time; As flux and cycling. By varying these parameters we investigate changes in the GaAs QD size, density and quality using atomic-force microscope (AFM) and low-temperature photoluminescence (PL). Our AFM results show a large QD size (with diameter of 150nm) can be obtained. PL at 5K shows strong emission from GaAs QDs. In-situ and ex-situ -annealing of samples in conjunction with radiative lifetime measurements shows that defects formed during the low-temperature growth can be removed.

3:50 PM Student

I7, Fabrication and Optical Characteristics of Type-II Self-Assembled GaSb Quantum Dots Embedded in InGaAs Quantum Well: Arezou Khoshakhlagh¹; Jun Tatebayashi¹; Ganesh Balakrishnan¹; L. R. Dawson¹; D. L. Huffaker¹; ¹University of New Mexico, Center for High Technology Materials

GaSb quantum dots (QDs) on GaAs have the potential to be used as the active material in optical sources, offering a wide range of emission wavelength especially at the telecommunication wavelength of 1.55 μm. Several groups have reported the optical properties of GaSb Stranki-Kranstano (SK) QDs emitting at 1.1 μm. However, it is necessary to control the emission wavelength of GaSb SK QDs in order to extend the light emission towards longer wavelength. In this report we study the optical properties of type-II GaSb SK QDs embedded in InGaAs quantum well (QW). We observe the redshift of the emission wavelength by using InGaAs layer instead of GaAs. Samples are grown on (100) semi-insulating GaAs substrates by solid-source molecular beam epitaxy. GaSb SK QDs are grown with a nominal thickness of 4 monolayers, and are capped with 7 nm InGaAs QW and 100 nm GaAs layer. Inserting a type I band structure, adjacent to the type-II QDs, will enable electrons to be trapped into InGaAs QW to lower the transition energy from the conduction band to the valence band. The insertion of type I InGaAs QW also increases the probability of electron-hole recombination by increasing the overlap of wavefunctions between electrons and holes. The photoluminescence (PL) properties of type-II GaSb SK QDs embedded in In_xGa_{1-x}As QW are studied by varying the Indium composition (x). The PL spectra of samples with different x show the existence of two main peaks. One peak emits at 1.13 μm, and the other peak emits at 1.205, 1.265 or 1.28 μm from the samples with x= 0.1, 0.2 or 0.3, respectively. The peak at 1.13 μm does not shift by changing the Indium composition of InGaAs QW, and the other peak shifts toward longer wavelengths by changing the Indium composition. The first stable peak at 1.13 μm is at the same exact wavelength that that of GaSb QDs capped with GaAs layer, which indicates that this peak corresponds to transition between holes confined within GaSb QDs and electrons in the GaAs conduction band. The second peak, which moves toward longer wavelengths by changing the Indium composition of InGaAs, is a result of transition between holes within GaSb QDs and electrons within InGaAs QW. The PL intensity of GaSb QDs in InGaAs QW is much stronger than that of GaSb QDs capped with GaAs due to the strong overlap of wavefunctions between electrons and holes. In summary, we have demonstrated controllability of the emission wavelength of type II GaSb QDs embedded in InGaAs QW by varying the Indium composition of a type I InGaAs layer adjacent the QD layer. This result may prove beneficial to a wide range of emission wavelength with one material system.

4:10 PM Student

I8, AlGaAs Microdisk Cavities with InAs Quantum Dots on Si and GaN: Fabrication and Near-Field Scanning Photoluminescence Characterization: Yaya Chu¹; A. Mintairov¹; Y. He¹; J. Merz¹; V. Tokranov²; S. Oktyabrsky²; ¹University of Notre Dame; ²Institute for Materials, State University of New York, Albany

Semiconductor discs with diameters of a few microns can be used to form whispering-gallery-mode (WGM) resonators. They can provide quality factors (Q) up to $\sim 10^5$ and are promising for low threshold micro-disk

lasers. Embedding quantum dots (QDs) into such high-Q micro-disk (MDs) cavities is promising for single photon sources and for studying cavity quantum electrodynamics effects. The traditional "mushroom-like" micro-disks (with a symmetric waveguide) suffer from poor heat-sinking and bad mechanical stability, which degrade the lasing performance of the micro-disk. To overcome these drawbacks, an asymmetric waveguide micro-disk design, based on wafer bonding to Si or GaN substrates, was used for the first time. High mechanical stability made it possible to use tapered fiber based near-field photoluminescence (NPL) to image optical fields in these cavities. An InAs/AlGaAs QD structure (QD density $\sim 5 \times 10^{10} \text{ cm}^{-2}$, emission wavelength $\sim 1.2 \mu\text{m}$ at 300K) was grown by molecular beam epitaxy on a GaAs substrate. The bonding procedure uses commercially available silicate glass (SOG) precursor (Filmtronics, Inc.) solution (dielectric constant ~ 2.5). After gluing the QD structure and Si wafers (or GaN epi-layers on a sapphire substrate) using a 600 nm-thick SOG, the back of the QD structure (GaAs substrate) was first manually polished down to 100 μm and then removed by H_2O_2 : NH_4OH (30:1) spray etch. The $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ etch stop layer was then removed using BHF. The resulting structure was used to fabricate micro-disk cavities having sizes 2-6 μm using e-beam lithography and reactive ion etching. Room temperature micro-photoluminescence measurements reveal sharp emission peaks related to WGM. The Q factors were estimated to be $\sim 10^4$. High spatial resolution NPL spectroscopy imaging in collection-illumination mode reveals clear structure related to WGM optical field distributions and allows the determination of azimuthal numbers (m) of the WGMs. The spectral and spatial dependence of the azimuthal numbers is analyzed and compared with numerical calculations based on 3D finite difference time domain methods. This is the first report of the use of wafer bonding with silicate glass to produce microdisk structures that are isolated from the substrate with a low refractive index glass film, which may have important applications to microdisk lasers. In this paper the materials properties and fabrication techniques will be emphasized.

4:30 PM

I9, Infrared Plasmon Resonance in Semimetallic Rare Earth-V/III-V Semiconductor Composite Materials: *Michael Scarpulla*¹; Micah Hanson¹; Elliott Brown²; Arthur Gossard¹; ¹University of California, Santa Barbara: Materials Department; ²University of California, Santa Barbara: Department of Electrical and Computer Engineering

Plasmon resonances in metal nanoparticles are the basis of many technologically-useful effects such as surface enhanced Raman scattering, enhanced Rayleigh scattering, and non-linear optical responses. To date most investigations of these phenomena have focused on metal nanoparticles where plasmon resonances lie in the visible to UV range. Here, we report resonant absorption in the infrared range (1-5 μm) in composite materials of semimetallic, rocksalt ErAs and ErSb nanoparticles (1-2 nm high by ~ 5 -20 nm laterally) embedded in GaAs and GaSb. The plasmon resonance is pushed into the infrared for these composites because of the high dielectric constant of the host semiconductor and the lower carrier concentration of the particles compared to metals. Resonant absorption in these composite materials is very strong; it exceeds the band edge absorption of the semiconductor host matrix in some cases. We report measurements on composite materials formed via two molecular beam epitaxy (MBE) growth modes; interrupted growth and continuous deposition. In the first mode, a layer of semimetallic islands is deposited and then overgrown by the host semiconductor resulting in a superlattice-like structure. In the later, the particles phase segregate during codeposition of Er and the host matrix. We demonstrate that the resonant absorption wavelength and intensity can be manipulated by the composition of the semiconductor matrix and by the MBE growth procedure and conditions. Furthermore, a polarization dependence is observed because of elongation of the particles along the [-110] direction. Finally, the prospects for similar nitride-based composite materials and their properties will be discussed.

4:50 PM

I10, White Light Emitting Solid State Hybrid Device of (CdSe)ZnS Quantum Dot-Near UV GaN LED: *Seonghoon Lee*¹; Aeeyoung Park¹; Wanki Bae¹; Kookheon Char¹; ¹Seoul National University

We produced (core)shell (CdSe)ZnS quantum dots by direct colloidal chemical synthesis through single step. Our newly developed single step synthesis of quantum dots with chemical composition (or energy gradient) is an

economic and straightforward way to get highly luminescent and photostable materials. The (CdSe)ZnS quantum dots play a role as a color conversion center. We fabricated white light emitting hybrid devices of (CdSe)ZnS QDs and a near UV GaN LED by combining (CdSe)ZnS quantum dots as a color conversion center with a near UV (NUV) GaN LED chip as an excitation source. This hybrid device has power efficiency of 22 lm/W.

Session J: Thermoelectric and Thermionic Heterostructures and Devices

Wednesday PM
June 20, 2007

Room: 131
Location: DeBartolo Hall

Session Chairs: Zhixi Bian, University of California, Santa Cruz; Eugene Fitzgerald, Massachusetts Institute of Technology

1:30 PM Invited

J1, Fabrication and Testing of Skutterudite-Based, Thermoelectric Devices for Power Generation Applications: *Jeff Sakamoto*¹; ¹California Institute of Technology/Jet Propulsion Laboratory

The Jet Propulsion Laboratory has led an intense effort to develop the next generation thermoelectric, power generators for NASA's future space missions. The emphasis has primarily been on thermoelectric technology employing Skutterudite-based modules and uncouples. This work includes segmenting with Bi_2Te_3 and other advanced materials. Specifically, two configurations comprise the effort: a heritage design employing uncouples that closely resembles Radioisotope Thermoelectric Generators (RTG) flown in Cassini, Galileo and both Voyager missions, and the second is an advanced design in which thermoelectric modules are conductively coupled to the heat source and heat sink. Although this is a new material system for NASA, the path to achieving efficient, reliable performance is practically the same as with previous technologies based on SiGe, PbTe or TAGS technology. Issues such as scalability, low-contact resistance, sublimation suppression, thermomechanical and thermal stability are all under evaluation. The Thermoelectrics team at JPL is currently addressing all of these issues and has fabricated and tested prototypes to validate conversion efficiencies in excess of 12% at the device level. JPL is also involved in work sponsored by Michigan State University and DOE to integrate similar technology into over the road vehicles to improve fuel efficiency.

2:10 PM Student

J2, Fabrication of Dense, Vertical Bi_2Te_3 Nanowire Array Composites for Thermoelectric Power Generators and Microcoolers: *Kalapi Biswas*¹; Manuel DaSilva¹; Vijay Rawat¹; Tim Sands¹; ¹Purdue University

The nanowire array configuration for thermoelectric materials offers advantages over thin films that include uniaxial transport properties, crystallographic texture control, enhanced thermoelastic compliance, improved access to surfaces and grain boundaries for post-growth doping and passivation, and increased freedom in the design of axial composition modulation without loss of lattice coherency. These design features have the potential to enable higher values of the thermoelectric figure-of-merit (ZT) when compared to bulk materials, thin films, and superlattices. Device applications – for example, thermoelectric power generators and microcoolers – require thick (>10 microns) thermoelectric elements to maintain the temperature difference and to overcome the effects of joule heating due to contact resistance. Furthermore, the nanowires must be embedded in a matrix with a thermal conductance that is small compared to the effective conductance of the nanowire array in order to minimize parasitic heat conduction. In this report, we describe a process for fabricating self-supporting nanowire arrays of textured Bi_2Te_3 using electrodeposition into a sacrificial porous anodic alumina (PAA) template. The electrodeposition method enables high-rate growth of single-phase, crystalline Bi_2Te_3 nanowires at room temperature, yielding nanowire arrays that are dense ($\sim 60\%$ volume fraction) with aspect ratios up to 800:1. X-ray diffraction and transmission electron microscopy analysis showed that the nanowires

have <110> texture, the orientation that yields the highest ZT in single crystals. This texture results from nucleation and growth on the vertical PAA pore walls. Following synthesis, the nanowire arrays are annealed and then mechanically planarized. A controlled etch-back process exposes the nanowire tips for metallization. The PAA template is then removed entirely by etching in a 3 wt% KOH solution to yield 40-micron-thick self-supporting Bi₂Te₃ nanowire arrays. The structural integrity of the nanowire arrays can be enhanced by infiltrating the array with poly-(methyl methacrylate) (PMMA), thereby replacing the PAA matrix with a mechanically tough and compliant material that has a thermal conductivity an order of magnitude lower than that of PAA. The thermal and electrical transport properties of these Bi₂Te₃ nanowire composites will be presented. This work was supported by a grant from the Office of Naval Research (N000140610641).

2:30 PM Student

J3, TiN/GaN and ZrN/ScN Metal/Semiconductor Rocksalt Nitride Superlattices for Thermionic Energy Conversion: *Vijay Rawat*¹; Tim Sands¹; ¹Purdue University

The possibility of using metal/semiconductor superlattices for thermionic energy conversion and solid-state refrigeration was proposed in the 1990's.^[1,2] Subsequent theoretical work showed that cross-plane transport through such metal/semiconductor superlattices has the potential to yield values of the figure-of-merit that are much higher than those of currently available thermoelectric materials.^[3] The primary challenge involved in realizing a solid-state thermionic energy converter is selecting materials suitable for fabrication of such superlattices. The integration of materials with disparate electrical and physical properties in superlattices with nanoscale periods requires consideration of several aspects of materials compatibility, including a) the similarity in crystal structures and lattice parameters necessary to initiate and sustain superlattice growth, b) the thermodynamic stability of the constituent materials at high operating temperatures required for thermionic generators (hot side temperatures of 300 to 650°C), and c) comparable surface and interfacial energies to maintain a Frank-van der Merwe (i.e. layer-by-layer) growth mode. Additionally, in order to achieve the highest possible energy conversion efficiency, the metal/semiconductor Schottky barrier height has to be optimized for the desired operating temperature range. Toward overcoming these challenges, we have identified two promising materials combinations for metal/semiconductor nitride superlattices, rocksalt TiN/GaN and ZrN/ScN, and have grown multilayers and superlattices of these materials with nanoscale periods using reactive pulsed laser deposition. Nitrides materials, being refractory in nature, are suitable for high temperature thermionic power generators. The first nitride superlattice system consists of TiN as the metal layer and GaN, in its metastable rocksalt phase, as the semiconductor layer, grown on rocksalt MgO substrates. The metastable rocksalt GaN (rs-GaN) phase is stabilized by pseudomorphic epitaxy on a metallic rocksalt TiN underlayer, and its existence has been verified using high-resolution x-ray diffraction and transmission electron microscopy. The critical thickness for the rocksalt-to-wurtzite phase transition has been empirically determined to be between 1 and 2 nm, although much thicker rocksalt GaN films, up to approximately 6 nm, can be maintained for several superlattice periods. The second rocksalt metal/semiconductor combination demonstrated in this study consists of ZrN as the metal layer and ScN as the semiconducting layer. Epitaxial films and multilayers of ZrN and ScN have been grown on MgO substrates using TiN film as a buffer layer. The electrical and thermal properties of the two metal/semiconductor superlattice systems will be presented, along with a discussion of the implications of the thermionic energy filtering for the performance of direct thermal-to-electrical generators. Acknowledgement: This work is supported by ONR/DOD through a multidisciplinary university research initiative (MURI) grant to the Thermionic Energy Conversion Center. ¹G.D.Mahan et. al., Phys. Rev. Lett., 80, 4016 (1998). ²A.Shakouri et. al. Appl. Phys. Lett., 71, 1234 (1997). ³A.Shakouri et. al. J.Appl. Phys., 95, 1233 (2004).

2:50 PM Student

J4, Non-Equilibrium Thermoelectric Transport in Thin Film Heterostructures: *Mona Zebarjadi*¹; Ali Shakouri¹; Keivan Esfarjani¹; ¹University of California, Santa Cruz

Several recent thermoelectric solid state devices are working in the

submicron length scale, where transport is neither completely diffusive nor completely ballistic. One can calculate pure diffusive and ballistic transports using simple approximations. But a more detailed analysis is required to investigate the thermoelectric transport in the intermediate regime. At the length scales of 100nm to 5 microns, Boltzmann transport equation is considered as a valid governing equation. A 3D Monte Carlo (MC) code has been developed with non-parabolic band structure. Acoustic, polar optical and nonpolar inter-valley optical phonons as well as ionized and neutral impurity scatterings are included to simulate the InGaAs family of materials. This MC code is coupled with a 1D Poisson solver to include electron-electron interaction. By using a new and fast algorithm, Pauli exclusion principle is enforced at each scattering step. This helps to find the correct electronic distribution inside the layers. The dissipated power to phonons is calculated and used to find the lattice temperature locally. Thermoelectric properties such as Seebeck coefficient depend on the size of the material when the hot and cold junctions are close to each other. We study the size and position dependence of thermal transport properties across a thin-film InGaAsP barrier layer sandwiched between two InGaAs contact layers. With decreasing size, the effective Seebeck coefficient is increased, because electrons do not have enough time to thermalize with the lattice. The transition between pure ballistic thermionic transport and fully diffusive thermoelectric transport is described. The energy and momentum relaxation lengths and their dependence on the applied field and the doping level are characterized. We find that the extend of the region in which Peltier cooling or heating happens near an interface is on the order of 0.1-0.4 microns for InGaAs material with a doping of $5 \times 10^{17} \text{cm}^{-3}$. Local electronic and lattice temperature, quasi Fermi-level, power dissipated to phonons, Seebeck coefficient and electronic thermal conductivity are calculated and the effect of interface will be discussed.

3:10 PM Break

3:30 PM Student

J5, Semimetallic Nanoparticles Epitaxially Embedded within III-V Semiconductors for Efficient Thermoelectric Power Generation: *Joshua Zide*¹; Gehong Zeng¹; Je-Hyeong Bahk¹; Woohul Kim²; Suzanne Singer²; Daryoosh Vashaee³; Zhixi Bian³; Rajeev Singh³; John Bowers¹; Arun Majumdar²; Ali Shakouri³; Art Gossard¹; ¹University of California, Santa Barbara; ²University of California, Berkeley; ³University of California, Santa Cruz

We present the growth of InGa(Al)As-based semiconductors (lattice-matched to InP) containing epitaxially embedded nanoparticles of semimetallic ErAs for use in efficient thermoelectric power generators. The incorporation of semimetallic nanoparticles into III-V semiconductors results in a composite with properties very different from the constituent materials, and it is possible to tailor these properties for a wide-range of properties, including thermoelectric power generation. The efficiency of thermoelectric materials is dependent on the figure of merit, $ZT = S^2\sigma T/\kappa$, where S is the Seebeck coefficient, σ is the electrical conductivity, and κ is thermal conductivity. Generally, these properties are interdependent. In recent years, nanostructured materials have been developed which have large ZT by reducing thermal conductivity. Generally, the thermoelectric power factor ($S^2\sigma$) is not substantially increased. We have demonstrated the reduction of thermal conductivity to below the so-called "alloy limit" without producing a highly defective material or reducing electrical conductivity. We have also demonstrated that it is possible to improve the thermoelectric power factor by introducing barriers, which filter electrons (by solid-state thermionic emission) and increases the Seebeck coefficient of a heterostructure with only a modest decrease in electrical conductivity. We present theoretical and experimental results for both ErAs incorporated into InGaAs/InGaAlAs superlattices (in which the InGaAlAs serves as the barrier to accomplish electron filtering) and also ErAs incorporated directly into InGaAlAs. In the latter case, electrons are filtered by buried Schottky barriers which are formed around the particles. In both geometries, thermoelectric efficiency is increased dramatically, especially at high temperatures. $ZT > 1$ has been measured at 600K and is expected to increase further at higher temperatures.

3:50 PM

J6, Micro Devices for Thermoelectric Figure-of-Merit Measurements of Thin Films: Zhixi Bian¹; R. Singh¹; Y. Ezzahri¹; M. Zebarjadi¹; A. Shakouri¹; G. Zeng²; J. Bahk²; J. Bowers²; J. Zide³; A. Gossard²; P. Mayer⁴; R. Ram⁴; ¹Electrical Engineering Department, University of California, Santa Cruz; ²Electrical and Computer Engineering Department, University of California, Santa Barbara; ³Materials Department, University of California, Santa Barbara; ⁴Research Laboratory of Electronics, Massachusetts Institute of Technology

There has been renewed interest in thermoelectric materials since low dimensional and nanometer structures were introduced. It is widely accepted that the thermal conductivity can be greatly reduced in these materials because of enhanced phonon scattering by interfaces and nano particles. It is also believed that the thermoelectric power factor can be increased if the electrical conductivity and the Seebeck coefficient can be engineered by optimizing the shape of the electronic band structure and the hot electron filtering. Several thin film materials with thermoelectric figure-of-merit (ZT) greater than 1 have been reported. However, the measurement data are usually dispersed. We discuss the key factors affecting ZT measurements using the transient Harman method. More specifically, we present the optimization of micro thermoelectric devices designed for ZT measurement of thin film materials. Because of the high device aspect ratios, several parasitic effects have to be considered. The electrical current uniformity and Seebeck voltage distribution are investigated by a self-consistent solution of the thermoelectric transport equation together with heat diffusion using the finite element method. When the electrical current pulse is injected from the top-side metal contact, the order of uniformity from low to high is: injection current density (and Peltier cooling density), electrical voltage, temperature, Seebeck voltage. The measured ZT at the side contact is smaller than the real material property due to current nonuniformity. For a 10 micrometer thick ErAs:InGaAlAs thin-film with 100 microns by 100 microns device area, the gold contact must be thicker than 10 microns in order to make the current uniform and the ZT measurement error smaller than 10%. The thermal leakage through the side contact should be minimized because it decreases the measured ZT value. A metal lead layer as thin as 0.2 microns with a neck narrowed down to 20 microns positioned 40 microns away from the film can reduce the thermal leakage and limit the extra ZT measurement error to 5%. The bottom metal contact should be thicker than 20 microns to reduce the parasitic ground contact resistance and current nonuniformity.

4:10 PM Student

J7, High-Temperature ZT of InGaAlAs Thin Films with Embedded ErAs Nanoparticles: Rajeev Singh¹; Zhixi Bian¹; Gehong Zeng²; Joshua Zide²; Woochul Kim²; Je-Hyeong Bahk²; Suzanne Singer³; Ali Shakouri¹; John Bowers²; Arthur Gossard²; Arun Majumdar³; ¹University of California, Santa Cruz; ²University of California, Santa Barbara; ³University of California, Berkeley

We have measured the thermoelectric (TE) figure-of-merit (ZT) of InGaAlAs thin films with embedded ErAs nanoparticles over a wide temperature range (300K-650K). This material system is currently being explored for use in power generation applications such as waste heat recovery. A novel high-speed measurement system was developed to measure the ZT of thin films of thicknesses on the order of 1um with a transient thermal signal resolution of 200ns at temperatures up to 900K. In order to resolve the intrinsic ZT of thin-film materials, TE devices were fabricated to minimize electrical and thermal parasitics and differential measurement was employed on TE devices of varying film thicknesses. The improvement in ZT of the material with ErAs nanoparticles embedded in the semiconductor matrix is verified throughout the temperature range. The increase in TE ZT is found to be mainly due to the reduction in material thermal conductivity due to phonon scattering by the ErAs nanoparticles.

4:30 PM

J8, Thin-Film Power Generator Modules of (InGaAs)_{1-x}(InAlAs)_x Embedded with ErAs Nanoparticles: Gehong Zeng¹; Je-Hyeong Bahk¹; John Bowers¹; Joshua Zide²; Arthur Gossard²; Zhixi Bian³; Rajeev Singh³; Mona Zebarjadi³; Ali Shakouri³; Woochul Kim²; Suzanne Singer⁴; Arun Majumdar⁴; ¹University of California, Santa Barbara; Department of Electrical and Computer Engineering; ²University of California, Santa

Barbara; Materials Department; ³University of California, Santa Cruz; Electrical Engineering Department; ⁴University of California, Berkeley; Department of Mechanical Engineering

We report a wafer scale approach for the fabrication of 400 element power generator modules composed of 200 n-type ErAs:(InGaAs)_{0.8}(InAlAs)_{0.2} and 200 p-type ErAs:InGaAs thermoelectric elements. Two sets of 400 element generator modules of 10 μm and 20 μm ErAs:(InGaAs)_{1-x}(InAlAs)_x alloy materials were fabricated using large scale integrated circuit compatible processing technology and flip-chip bonding techniques. The output power of 1.12 W/cm² and open circuit voltage of 2.1 V were measured for 10 μm generator modules with a temperature difference of 24 K across the elements; an output power of 2.5 W/cm² and open circuit voltage of 3.5 V were measured for 20 μm generator modules when the temperature difference across the generator elements was 39 K. Device modeling was carried out to get a better understanding of the performance of these thin film generator modules, and the calculation results indicate that the performance of thermoelectric generator modules can be further improved by optimizing the fill factor of the generator modules, increasing the thicknesses of the elements, and reducing electrical and thermal parasitic resistance. The incorporation of ErAs metallic nanoparticles into the InGaAlAs structure can provide charge carriers, produce local Schottky barriers for electron filtering, and create effective scattering centers for middle and long wave phonons. Therefore the material's figure of merit $Z = \alpha^2 \sigma / k$ can be improved by a lower thermal conductivity k , an enhanced Seebeck coefficient α , and a high electrical conductivity σ . The thermoelectric properties of the ErAs:(InGaAs)_{1-x}(InAlAs)_x alloy vary with ErAs nanoparticle concentrations, the composition ratio of InGaAs to InAlAs, and co-doping values etc. Material optimization is still underway. With further improvements on material thermoelectric properties, processing technology and the optimization of the generator module configuration, an output power up to 10 W/cm² is possible.

4:50 PM

J9, Late News

Session K: Silicon Carbide: Devices and Processing

Wednesday PM

June 20, 2007

Room: 138

Location: DeBartolo Hall

Session Chairs: Michael Capano, Purdue University; Robert Stahlbush, Naval Research Laboratory

1:30 PM Invited

K1, Some Critical Materials and Processing Issues in SiC Power Devices: Anant Agarwal¹; ¹Cree, Inc.

There has been a rapid improvement in SiC materials and power devices in recent years. However, the materials community has over-looked some critical issues which may threaten the emergence of SiC power devices in the future. Some of these pressing materials and processing issues are discussed in this paper. The phenomenon of recombination-induced stacking faults (SFs) in high voltage p-n diodes in SiC has been shown to increase the forward voltage drop due to reduction of minority carrier life-time. We have recently discovered that this effect is equally important in unipolar devices such as high voltage MOSFETs and MPS diodes. If the internal body diode is allowed to be forward biased during the operation of these devices, then the recombination induced SFs not only reduce the majority carrier conduction current but also significantly increase the leakage current in blocking mode. The effect is more noticeable in high voltage devices where the drift layer is thick, and is not expected to impact 600-1200 V devices. The consequences of this finding will change the way majority carrier devices in SiC are designed and used. Furthermore, the traditional understanding that the formation of SF in SiC affects only the bipolar devices has been proven wrong. Some of the most important issues limiting the commercialization of SiC power MOSFETs are low threshold voltage, low effective inversion layer mobility and poor reproducibility of these very important parameters from run to run.

All these problems are inter-related. The conventional understanding is that the high fixed positive charge in the gate dielectric is balanced by an equally high negative charge in the acceptor-like states near the conduction band edge, resulting in low and poorly reproducible threshold voltage. The high density of interface states not only remove the inversion layer electrons from the conduction band but also reduce their effective mobility by scattering. It will be shown, for the first time, that an important third component of this problem, which has been over-looked thus far, also significantly affects the threshold voltage and effective inversion layer electron mobility. This component is due to the bulk traps in SiC which may already be present in high numbers and are significantly increased by processing such as ion-implantation and high temperature anneals. Furthermore, these bulk traps may be related to recombination-induced SFs in the inversion layer. If this theory is correct then research efforts must shift from reducing the interface state density at the SiC/SiO₂ interface using various pre-oxidation and post-oxidation anneals to reduction of process-induced bulk traps in SiC. The process of fabrication of MOSFETs may shift toward utilizing epitaxial layers as opposed to the implanted p-wells and subsequent activation at temperatures as high as 1700°C.

2:10 PM

K2, Effects of Threading Screw, Threading Edge, and Basal-Plane Dislocations on the Electrical Properties of 4H-SiC Schottky Diodes: *Brian Skromme*¹; *Y. Wang*¹; *M. K. Mikhov*¹; *V. Varshney*¹; *S. Mahajan*¹; ¹Arizona State University

The high breakdown field, Schottky barrier height, and thermal conductivity of 4H-SiC make it a very useful material for the fabrication of low switching loss Schottky diode rectifiers. However, crystal defects are believed to limit the yield and performance of devices made on this material, especially in large-area devices. The impact of different types of defects on device performance has however been controversial, and a clear understanding of this issue has yet to emerge. Here, we use a combination of current-voltage (I-V) measurements under forward and reverse bias, electron beam-induced current (EBIC) measurements, molten KOH defect etching, and analytical modeling to analyze the effects of various dislocation types on the breakdown voltage, barrier height, and ideality factor of Ni Schottky diodes on 4H-SiC(0001). The 0.2-1.0 mm diameter diodes were formed on 10 μm thick epitaxial layers doped in the N_D = 5-7x10¹⁵ cm⁻³ range using a shadow-mask process without edge termination. Defects were identified based on the characteristic different etch pits produced by small screw dislocations (SSDs), threading edge dislocations (TEDs), and basal-plane dislocations (BPDs). A one-to-one correspondence is found between the isolated dark spots observed in EBIC and SSDs and TEDs. The BPDs produced elongated comet-like features in EBIC, consistent with the 8° misorientation from (0001). Diode ideality factors and barrier heights are found to be directly related to the concentration of dark spots in EBIC (due to SSDs and TEDs). A statistical analysis of variance is used to determine the relative influences of each of the three dislocation types on breakdown voltage (V_{br}) in devices lacking obvious morphological defects or micropipes. Both SSDs and BPDs have statistically significant effects on V_{br}, but isolated TEDs do not (with the exception of those arranged in subgrain boundaries). The effect of a BPD is about twice that of a SSD. Interactions between dislocations do not significantly affect V_{br}. A comprehensive model is developed to fit the observed forward and reverse I-V characteristics and explain the influence of the dislocations. The model posits low barrier height patches surrounded by high barrier height regions, each patch arising from a SSD or BPD. Lateral potential pinch-off is modeled using Tung's theory of laterally inhomogeneous barriers and found to be important in forward and small reverse bias. For reverse bias above about 10 V, potential pinch-off ceases to occur and a model including thermionic field emission and Frenkel-Poole emission from near-surface traps into conductive dislocations is used, including the low barrier height patches as parallel diodes. Both forward and reverse I-V properties are successfully explained with this model. The conductive dislocations and associated interface traps explain the origin of the low effective barrier height patches.

2:30 PM Student

K3, Evidence of Negative Bias Temperature Instability in 4H-SiC Metal Oxide Semiconductor Capacitors: *Matthew Marinella*¹; *D. Schroder*¹; *T. Isaacs-Smith*²; *A. Ahyi*²; *J. Williams*²; *G. Chung*³; *J. Wan*³; *M. Loboda*³; ¹Arizona State University; ²Auburn University; ³Dow Corning Compound Semiconductor Solutions, LLC

In recent years, a great deal of work has gone into the optimization of the SiC/SiO₂ interface in order to create a density of interface states (D_{it}) suitable for the fabrication of MOS devices. However, an important effect which is known to degrade the Si/SiO₂ interface has not been thoroughly studied in the SiC/SiO₂ system.^{1,2} This effect, known as negative bias temperature instability (NBTI), causes a negative threshold voltage shift, degrades channel mobility, and reduces drain current in silicon MOSFETs. Although the exact mechanism which causes NBTI is not fully understood, it is generally believed that the effect requires a negative gate voltage and holes in the semiconductor. In our research, anomalous behavior that we have observed when making lifetime measurements can be explained by NBTI. MOS capacitors were fabricated from n-type 4H-SiC samples with a 450 nm thermal oxide. Generation lifetimes were measured using the pulsed MOS capacitor (MOS-C) technique at 400°C. This technique involves biasing a MOS-C into deep depletion and monitoring the capacitance change during the generation of the inversion layer. The data can then be used to calculate an effective generation lifetime for the material. In the present experiments, when multiple pulsed MOS-C tests were performed consecutively, the effective generation lifetime decreased significantly after each measurement. Under normal circumstances, this characterization technique should not cause a change in lifetime. Furthermore, following each pulsed MOS-C test, capacitance-voltage (C-V) and conductance-voltage (G-V) measurements indicated an increase in D_{it}. This behavior can be explained by assuming that holes in the inversion layer cause the increase in D_{it} as a result of the NBTI effect. The increased number of interface states leads to a higher surface generation velocity and a lower effective lifetime, as observed. Further measurements made at a temperature too low for an inversion layer to form did not exhibit this degradation, confirming that holes are needed for the increased D_{it} to occur. Therefore, this behavior is consistent with the known behavior of NBTI in silicon. A portion of the lifetime degradation caused by this effect can be recovered by removing the negative bias as well as by positively biasing the device. This effect should be considered when making generation lifetime measurements in n-type SiC material using the pulsed MOS technique, as it will cause lifetimes to appear artificially short. In addition, the ensuing D_{it} increase associated with NBTI is detrimental to the mobility of a SiC p-MOSFET, especially if high temperature operation is desired. This work was supported in part by ONR Contract #N00014-05-C-0324 (Program Officer: Dr. Colin Wood). ¹D.K. Schroder and J.A. Babcock, *J. Appl. Phys.* 94, 1 (2003). ²M. Bassler, V.V. Afanas'ev, G. Pensl, and M. Schultz, *Microelectron. Eng.* 48, 257 (1999).

2:50 PM

K4, The Effects of Implant Activation Anneal on the Effective Inversion Layer Mobility of SiC MOSFETs: *Sarah Haney*¹; *Mrinal Das*¹; *Anant Agarwal*¹; ¹Cree, Inc.

The reduction of interface states in SiC MOS system has been a focus of research during the past decade. Low effective inversion layer mobility (μ_{neff}) of electrons has been shown to be due to the high D_{it} near the conduction band of an n-channel 4H-SiC MOSFET. Here, we show the detrimental effect of implant activation anneal on the μ_{neff} of lateral 4H-SiC MOSFETs. In this experiment, lateral n-channel MOSFETs were fabricated on 1e10¹⁶ cm⁻³ Al-doped p-type epilayers grown on p-type 4H-SiC substrates off-cut 8° from the (0001) Si-face vicinal surface. Phosphorus was implanted to form the source and drain regions. Gate oxide was grown at 1175°C Dry O₂, followed by 950°C Wet O₂ and 1175°C NO anneals. Boron doped Poly-Si films formed the gate electrode. Nickel contacts were made to the source and drain. A 200 μm x 200 μm channel was designed to isolate the channel resistance so that the field effect mobility can easily be extracted from the transconductance. Four process splits were investigated: (a) MOSFET annealed at 1300°C to activate the implants in the source and drain. This MOSFET displayed the best peak μ_{neff} of 46 cm²/V-s. (b) Same as (a) however the source and drain implants were activated at 1650°C in Silane overpressure to minimize the surface roughness. The peak value of μ_{neff} decreased to 30 cm²/V-s and the

threshold voltage increased as compared to (a). (c) Same as (b) however a p-well was implanted with Al and activated at 1650°C in Silane overpressure along with the implants for source and drain. This case had the lowest peak mobility of 22 cm²/V-s and highest threshold voltage. (d) Same as (c) however the wafer was coated with graphitized photoresist and activated at 1650°C in Ar. Results were similar to (c) even though the RMS surface roughness was dramatically reduced. Here, the reduced mobility was accompanied by an increased threshold voltage, indicating an increase in negative charge in the semiconductor. The results can be explained by either an increase in D_{it} or an increase in the bulk trap density in SiC. It may be fair to speculate that whatever mechanism gives rise to increased D_{it} is also likely to increase the bulk traps in SiC. Regardless, if the surface change is due to the high temperature anneal, it is removed in subsequent sacrificial oxidation step. The SiC-SiO₂ interface is made on the fresh surface of SiC after consuming a certain amount of SiC layer during the oxidation process. This point is reinforced by the results of splits (c) and (d), where reduction in the surface roughness did not impact the device turn-on characteristics. More tests are currently being conducted.

3:10 PM Break

3:30 PM

K5, 1200 V 4H-SiC Bipolar Junction Transistors with a Record β of 70: Charlotte Jonas¹; Craig Capell¹; Al Burk¹; Qingchun (Jon) Zhang¹; Robert Callanan¹; Anant Agarwal¹; ¹Cree, Inc.

In this paper, a common current gain of 70 has been achieved on 4H-SiC Bipolar Junction Transistors (BJTs) at room temperature, which is the highest among reported. BJTs have an active area of 3 mm x 3 mm. At 25°C, an on-current of 35 A was observed at a forward drop of 1.4 V, which corresponds to a specific on-resistance of 3.6 m Ω -cm². BJTs exhibit a positive temperature coefficient in specific on-resistance. At 250°C, the collector current decreases to 18.7 A at 2.6 V with a current gain of 42, which corresponds to 12.5 m Ω -cm² of specific on-resistance. BV_{CEO} and BV_{CBO} of 1200 V were observed at < 5 mA leakage currents at all temperatures up to 250°C. BJT dynamic characteristics were conducted by using the IXYS RF/Directed Energy IXDD415 gate driver evaluation board to drive the BJT. A V_{CE} fall time at turn-on time of 15 nsec was measured with 2 A of a gate current provided to support a collector current of 63 A. A V_{CE} rise time at turn-off was 11 nsec was achieved. Abundant work has been conducted on device degradations in both on-resistance and current gain. It has been observed that the base-emitter surface properties were attributed to the on-resistance degradation. A surface passivating SiC layer was grown on SiC and it covers the emitter mesa sidewall and the space between the emitter and the base implant region. The thickness and doping of this layer is chosen such that the layer is fully depleted at zero bias. Experimental results have shown that 4H-SiC BJTs with such a layer have a stable on-resistance after stress. More degradation measurement and analysis are in progress and the results will be presented at the time of the conference.

3:50 PM Student

K6, Terahertz Emitting Devices Based on Hexagonal Silicon Carbide: Guangchi Xuan¹; Pengcheng Lv¹; Xin Zhang¹; James Kolodzey¹; Greg DeSalvo²; Adrian Powell³; ¹University of Delaware; ²Northrop Grumman; ³Cree Inc.

In recent years, due to increasing interest in the Terahertz (THz) frequencies for ranging, imaging, spectroscopy and telecommunication applications, sources between 0.1 and 10 THz (3mm – 30 μ m) have attracted much attention. THz emission from radiative transitions between impurity states have been demonstrated in silicon devices by either electrical or optical pumping. These devices are very attractive due to their simple device design (no need for quantum wells) and low cost. However, the silicon-based devices are limited by a maximum operating temperature of 90K due to thermal quenching. Group IV wideband gap compound semiconductor SiC exhibits several advantages compared to the Si materials. Impurity activation energies in both Al-doped and N-doped SiC are higher than that of the Si; therefore the maximum operating temperature is relatively high and emission at 150 K was observed. Combining with its superior material qualities such as high breakdown field and high thermal conductivity, SiC is a promising material for Terahertz emitting devices based on dopant transitions. We are reporting THz emitting devices fabricated on hexagonal (4H- and 6H-) SiC

materials. The current dependence and temperature dependence of the emitted THz spectra will be studied. We will also report on the spectral output power relationship with pumping conditions. Our results show that the working temperature of our SiC-based devices exceeds the highest reported for THz quantum cascade lasers, and was much higher than any Si-based devices operating on the dopant transitions. It suggests that doped SiC is a strong material candidate for high power and high operating temperature THz source devices.

4:10 PM Student

K7, Nitrogen Doping for Low-Temperature Halo-Carbon Homoepitaxial Growth of 4H-SiC: Kritsa Chindanon¹; Huang-De Lin¹; Yaroslav Koshka¹; ¹Mississippi State University

Recent developments in the low-temperature homoepitaxial growth technique utilizing halo-carbon growth precursor enabled good-quality 4H-SiC epitaxial layers at temperatures down to 1300°C and below. A rising interest in this method was further enhanced by (1) demonstration of low-temperature selective epitaxial growth (LTSEG) conducted with SiO₂ mask, which had been considered impossible for 4H- and 6H-SiC homoepitaxy, and (2) demonstration of very efficient n+ and p+ doping of C-face and Si-face epitaxial layers respectively. Utilization of low-temperature epitaxial growth (and LTSEG in particular) for device applications requires knowledge of the main process dependencies for dopant incorporation. Prior to this work, there had been almost no data on nitrogen incorporation during 4H- or 6H-SiC homoepitaxy in the temperature range below 1400°C. In this work, intentional nitrogen doping was performed during low-temperature halo-carbon epitaxial growth conducted on Si- and C-faces of 4H-SiC substrates in a low-pressure hot-wall CVD reactor. The dependencies of nitrogen incorporation on nitrogen flow, Si/C ratio, growth rate, and temperature were investigated. It was established that the efficiency of nitrogen incorporation for the C-face growth at 1300°C may be 3 orders of magnitude higher than for the Si-face (especially at low growth rate and low Si/C ratio). Nitrogen concentrations in excess of 10²⁰ cm⁻³ were achieved in the C-face epi, with high percentage of dopant activation and without morphology degradation. For the Si-face epi, the dependence of nitrogen incorporation on Si/C ratio was consistent with the “site-competition” model (i.e., the n-type doping increased with increasing the Si/C ratio). However, an unusual feature of the low-temperature epitaxy was a saturation of nitrogen incorporation at high silane flows (high Si/C ratios). The observed saturation further confirmed the critical role of the silicon vapor condensation mechanism during the low-temperature epitaxy. Silicon vapor condensation limits supply of silicon ad-species to the growth surface. As a result, the “effective” Si/C ratio at the growth surface reaches its saturation value and does not increase any more at high silane flows even when the “input” Si/C ratio is further increased. Nitrogen doping during the growth on the C-face showed much weaker dependence on the Si/C ratio, which is consistent with prior results of regular-temperature epitaxial growth. The nitrogen doping dependence on the growth rate showed a trend opposite to what had been previously reported for epitaxial growth processes conducted at regular temperatures. Increasing the growth rate caused strong increase of nitrogen doping on the Si-face and a decrease of nitrogen doping (though less pronounced) on the C-face. Finally, complex temperature dependence in the temperature range from 1300 to 1450°C was observed. The differences of the temperature dependence in our low-temperature range from the trends previously reported for the higher-temperatures epitaxial growth will be discussed.

4:30 PM

K8, Impact of Thickness and Nitrogen Doping on Carrier Lifetime in 4H-SiC Epilayers: Kok-Keong Lew¹; Brenda VanMil¹; Rachael Myers-Ward¹; Paul Klein¹; Michael Mastro¹; Joshua Caldwell¹; Larry Wang²; Ronald Holm¹; Charles Eddy¹; D. Gaskill¹; ¹Naval Research Laboratory; ²Evans Analytical Group

Recently, there has been significant progress in producing 4H – silicon carbide (SiC) devices. For high performance in bipolar power devices, it is desired to have long minority carrier lifetime in the range of microseconds and low background carrier concentration (< 10¹⁴ cm⁻³) in the thick n- drift region. However, few studies relating these device layer features (thickness and doping) to carrier lifetime have been reported. In this paper we report such a study. An Aixtron/Epigress VP508 hot-wall chemical vapor deposition

(CVD) reactor was used for the epitaxial growths. Silane (SiH_4 , 2% diluted in H_2) and pure propane (C_3H_8) were used as silicon and carbon sources, respectively. Research grade, 4H-SiC, n^+ -type substrates offset 8° toward the $\langle 11\text{-}20 \rangle$ direction were used for the experiments. Before loading into the CVD reactor, the substrates were subjected to a cleaning procedure,¹ x-ray diffraction² and cross-polarization wafer mapping.³ Growths were conducted at 1580°C and the reactor pressure and H_2 flow were at 100 mbar and 80 slm, respectively. The net carrier concentration was determined using capacitance-voltage profiling with a mercury probe and further impurity analysis was measured by secondary ion mass spectrometry (SIMS). Room temperature carrier lifetimes were measured using the decay of the excitation/ band edge photoluminescence (PL) peak at 391 nm. Lifetime measurements by microwave photoconductivity decay (μ -PCD) mapping are also presented in this study. An optimal growth rate of $10 \mu\text{m/hr}$ and a set of substrates from the same SiC boule were chosen for the carrier lifetime experiments. The standard structure was a $5\text{-}\mu\text{m}$ thick n^+ ($> 10^{18} \text{cm}^{-3}$) buffer layer followed by an unintentionally-doped i -layer with varying thicknesses and n -type dopings ranging from 5×10^{13} to $5 \times 10^{14} \text{cm}^{-3}$. PL carrier lifetimes showed an increase from 525 to 800 ns as the thickness varied from 10 to $38 \mu\text{m}$. Lifetimes from μ -PCD were usually a factor of 2 to 3 higher than those measured via PL. For $20\text{-}\mu\text{m}$ unintentionally-doped epilayers, a low background carrier concentration ($\sim 5 \times 10^{13} \text{cm}^{-3}$) had a lifetime of 790 ns compared to 550 ns for the same structure, but with $\sim 9 \times 10^{13} \text{cm}^{-3}$ background carrier concentration. However, intentionally nitrogen-doping the i -layer to $\sim 2 \times 10^{14} \text{cm}^{-3}$ resulted in an enhanced PL lifetime of $1.2 \mu\text{s}$ for the same structure. This improvement could be useful in future device performance. Further studies will be conducted to understand the effect of low nitrogen concentration doping on the deep level trap concentration and carrier lifetime. ¹K.-K. Lew *et al.*, accepted for publication in Materials Science Forums. ²M. A. Mastro *et al.*, J. Appl. Phys. 100, 93510 (2006). ³D. K. Gaskill *et al.*, accepted for publication in Materials Science Forums.

4:50 PM

K9, Real-Time, In-Situ Tracking of Gas Phase Carbon-to-Silicon Ratio during Hot-Wall CVD Growth of SiC: Brenda VanMil¹; Kok-Keong Lew¹; Rachael Myers-Ward¹; Charles Eddy¹; D. Gaskill¹; ¹U.S. Naval Research Laboratory

The carbon-to-silicon ratio influences the background doping level of silicon carbide (SiC) grown by hot-wall chemical vapor deposition (HWCVD).¹ Typically a C/Si ratio of ~ 1.5 gives a minimum n-type background less than $1 \times 10^{14} \text{cm}^{-3}$, however, the actual ratio for such background carrier levels varies from system to system. Higher ratios typically result in type conversion to p-type backgrounds while lower values give higher n-type backgrounds. Minimal background levels are desired for power electronic device applications, for example, blocking or drift layers in high voltage diodes and switches. Such layers can be in excess of 100 micrometers thick and can require tens of hours to grow. The effective C/Si ratio must be precisely controlled throughout these long epitaxial growths to achieve optimal device performance. A method to measure and control the C/Si ratio during growth would enhance the performance of high voltage devices and their yield. Mass spectra were sampled *in-situ* with a Hiden Analytical HPR-20 QIC Gas Analysis System quadrupole mass spectrometer downstream of the reaction zone in a commercial Aixtron/Epigress VP508GFR HWCVD SiC reactor. Mass spectra were taken of SiC growth precursors, namely silane and propane, independently and together through the reaction zone at temperatures of 1000°C , 1400°C and 1580°C . The 26 amu mass-to-charge peak associated with acetylene showed the most dynamic response to intentional changes in precursors at the growth temperature of 1580°C , and thus the C/Si ratio. Methane peaks also show a similar, but smaller dynamic response. Growth experiments were performed by holding one precursor constant and varying the second precursor. The acetylene peaks have a direct linear correlation to variations in the propane and silane precursors, and thus can be tracked to give real time *in-situ* measurement of changes in the C/Si ratio. *In-situ* real-time tracking of acetylene can be implemented as a feedback control for precursor inlet flows to actively control the C/Si ratio. Monitoring the magnitude of an acetylene peak measures the resulting products of reactions in the system, which is influenced by many real variations of the system including drift of the introduced precursors, degradation of components of the system, decomposition of SiC deposits,

and changes in temperature distribution. Changes in hot spots in the reaction zone may also affect the hot-zone thermal profile, influencing the decomposition of the precursors. These can impact the effective C/Si ratio at the growth interface, altering the background carrier concentration. This *in-situ* diagnostic permits real-time adjustment of growth parameters, during SiC growth by hot-wall chemical vapor deposition, enabling tighter control of intrinsic doping characteristics of unintentionally doped SiC films for enhanced carrier lifetime and performance of high power and high voltage power electronic devices. ¹Chen *et al.*, J. Appl. Phys. 98, 114907 (2005).

Session L: Materials Integration and Flexible Thin Film Electronics

Thursday AM
June 21, 2007

Room: 126
Location: DeBartolo Hall

Session Chairs: Karl Hobart, Naval Research Laboratory; William Wong, Palo Alto Research Center

8:20 AM Student

L1, Fabrication of Transfer-Enhanced Substrates by Wafer Bonding and Hydrogen Exfoliation Techniques: *Monali Joshi*¹; Sumiko Hayashi¹; Daniel Law²; Mark Goorsky¹; ¹University of California, Los Angeles; ²Spectrolab, Inc.

An engineered Transfer-Enhanced Semiconductor substrate (TES) was fabricated with an embedded porous layer to promote transfer of device layers after device fabrication. This composite substrate can serve as an epitaxial template for electronic, optoelectronic, and photovoltaic devices and would allow the expensive substrate material to be reused. Moreover, the design of the template promotes the transfer of the thin device layers to another substrate, enabling innovative device applications such as flexible solar cells and novel integration schemes such as transfer of device layers from a specific lattice parameter substrate to, for instance, a high resistivity substrate. A silicon handle substrate wafer was subjected to anodic etching to produce a thin, lower density porous layer at the surface which serves as a mechanically weak layer. Next a hydrogen ion implanted InP wafer was wafer bonded to the handle wafer via silicon nitride interlayers. The RMS roughness of the porous surface was found to be 0.5 nm, and the PECVD nitride layer was found to be conformal with an RMS surface roughness of 0.8 nm; as such no chemical mechanical polishing (CMP) was necessary prior to bonding. Transfer of the InP layer was accomplished through hydrogen exfoliation. The InP wafer was implanted with a dose of 5×10^{16} H²/cm² at 150 keV at -20°C. The bonded wafers were annealed for 8 hours at 150°C to strengthen the bond and subsequently annealed at 300°C to induce exfoliation. The transferred layer was characterized using AFM, triple-axis x-ray diffraction (TAD) measurements. The results were compared with a bare InP wafer and an exfoliated InP layer on bare Si to assess any effect of the underlying porous layer on the InP layer crystal quality. As exfoliated, the transferred InP layer had an RMS surface roughness of 29 nm and a TAD FWHM of 39 arcseconds, indicating some residual surface damage. A CMP process consisting of sodium hypochlorite and citric acid solutions was used to remove surface damage, and an RMS roughness of 0.6 nm was achieved. The TAD FWHM after polishing was 31 arcsec, indicating that the composite structure may be used for further device fabrication. This procedure for fabricating TES structures can be applied to produce other III-V composite structures.

8:40 AM Student

L2, Selective Debonding of InN from Sapphire to Form Electronically Active Structures: *Dong Hao*¹; William Schaff¹; Lester Eastman¹; ¹Cornell University

Indium Nitride is a very important material due to its high electron mobility, and compatibility with GaN. This compatibility could potentially utilize the full visible spectrum, creating highly efficient LEDs and solar cells. However, InN surface electron accumulation has prevented the fabrication of electronic devices. A novel technique is used to debond the InN film from the Sapphire substrate, and was then bonded onto various host substrates. Electrical and optical properties were measured, consistent with that of crystalline InN. InN was placed film side down onto the host substrate with the sapphire substrate facing the laser. A 1060nm infrared pulsed laser operating at 20-40 kHz was used to heat up and debond the InN with a focal beam size of 50µm. Laser line speeds ranging from 10-500 mm/s were used with the laser operating in parallel and crosshatch fill mode. InN squares with lengths ranging from 200µm to 4mm were bonded to substrates of Si (p-type), GaAs, InP, and Titanium. The InN squares were then

characterized by Photoluminescence (PL). Under some bonding conditions a PL peak of 2000nm was observed confirming the presence of crystalline InN. IV characterization of n-type InN deposited onto p-type Si showed rectifying behavior consistent with a heterojunction. A current source was applied to the heterojunction with preliminary results showing a spectrum peak at 1600nm. These results are consistent with the Electroluminescence (EL) spectrum that would be expected from InN where the emission peak has shifted due to band filling. This approach to fabricating InN/Si devices shows different electrical behavior than from InN grown directly onto Si. InN grown on Si results in a leaky interface due to electronic defects. However, even with the likely existence of surface electron accumulation at the bonding InN/Si interface, rectifying behavior was still observed using the laser debonding technique. In the future, this technique could potentially be expanded to other material systems with transparent substrates as a new means of creating heterogeneous active integration.

9:00 AM

L3, Low Temperature Wafer Bonding for III-V Si Photonic Integrated Circuits: *Di Liang*¹; Hyundai Park¹; Alexander Fang¹; John Bowers¹; ¹University of California, Santa Barbara

VLSI Photonics is an important research direction that is driven by the need for increasing circuit complexity and chip functionality as well as lower cost photonic integrated circuits. Recently, lasers, amplifiers and photodetectors have been demonstrated using evanescent coupling from Si optical waveguides to III-V materials. A key problem is to develop a low temperature bonding process between Si and III-V materials that is CMOS compatible and scalable to 150 mm wafers. In this paper, strong bonding between thermal SiO₂ grown on 100 mm diameter silicon-on-insulator (SOI) wafers and chemical vapor deposition (CVD) SiO₂ on InP wafers is demonstrated at low temperatures ($\leq 300^\circ\text{C}$). A key parameter for evanescently coupled photonic circuits is to keep the SiO₂ layer less than 100 nm thick for strong coupling between the Si waveguide and III-V gain and absorption layers. A thin deposited oxide is also preferred to minimize the surface roughness to < 1 nm, eliminating the need for chemical mechanical polishing. Two approaches are employed to achieve a bubble-free bonding interface. The first approach involves growing thin (< 50 nm) thermal SiO₂ to allow moisture easily penetrating through the oxide and react with the Si beneath, forming Si-O-Si covalent bond, and the byproduct H₂ can diffuse along the interface by patterning the SOI wafer with channels. The bubble density is proportional to the oxide thickness due to the slower diffusion rate of H₂O over H₂ molecules. The bubble density for this method is also dependent on channel density which in turn may be influenced by the silicon device layout. The bubble density is measured under a microscope after selectively removing the InP substrate. Treating the SiO₂ surfaces with dilute HF ($< 0.5\%$) solution is shown to be another valid approach to obtain high quality bonding. A one minute HF dip immediately prior to room temperature contact results in the breaking of Si-O-Si rings and the formation of large fluorinated silicon oxide (SiOF) rings. The highly porous structure facilitates the diffusion of impurities and enhances moisture absorptivity, effectively reducing the out-gassing rate. The bonding strength dependence on CVD SiO₂ quality is also studied by comparing conventional PECVD SiO₂ deposited at 250°C and high-density inductively coupled plasma (ICP) PECVD SiO₂ at 100°C with the same thickness. Higher refractive index and smoother surface are found in ICP PECVD SiO₂, indicating a superior quality, which subsequently resulted in a stronger bonding interface energy. All bonding experiments were performed in an N₂ gas ambient for 3 hours using a Karl Suss wafer bonder. We report on the impact of scaling the bonding process to 100 mm wafers via these two wafer bonding processes on hybrid silicon evanescent laser performance.

9:20 AM Student

L4, From (001) Silicon Direct Wafer Bonding to the Surface Nano-Patterning for the Self-Assembled Growth of Nanostructures: *Alexis Bavard¹; Alina Pascale²; Jérôme Mézière¹; Gilles Renaud²; Frank Fournel¹; Joël Eymery³; ¹Léti-Minatec Commissariat à l'Énergie Atomique Grenoble; ²Commissariat à l'Énergie Atomique, Grenoble and Département de Recherche Fondamentale sur la Matière Condensée/SP2M; ³Commissariat à l'Énergie Atomique Grenoble, Département de Recherche Fondamentale sur la Matière Condensée/SP2M, Commissariat à l'Énergie Atomique-Centre National de la Recherche Scientifique Research Group*

Self-assembled configurations of nanostructures are expected to play an increasingly important role in devices design, as an alternative to conventional microelectronics technology. Conventional techniques are generally limited by the lack of simultaneous control on positioning, density and size uniformity of the nanostructures. To overcome these problems a new template based on controlled direct twist wafer bonding and preferential chemical etching has been developed. The proposed process consists in using a thermally oxidized Silicon-On-Insulator (SOI) substrate with a ~ 1 μm thick (001) Si film previously patterned by deep graduated scales to produce two SOI wafers with twin surfaces,^{1,2} i.e. with the same miscut. Then they are directly rebonded together with a twist angle (Ψ) introducing, after a high-temperature annealing, a nearly pure square Dislocation Network (DN) at the bonding interface which can be tuned using Ψ . After various thinning processes a SOI structure including the buried DN into the Si thin film is obtained. By using a dislocation preferential chemical etching (HF/H₂O/CrO₃)³ the surface can be nanopatterned. However, the trenches depth obtained after this selective etching (~ 1.5 nm) are generally not enough to position nanostructures (such as Ge dots⁴). A second selective chemical etching can be applied (CH₃COOH, HNO₃, HF)⁵ to both improve the trenches depth and to remove the buried DN. We will present 20 nm and 50 nm periodicity samples with ~ 4 nm trenches depth measured by STM tip and High Resolution TEM where the initial bonded crystal has been completely removed as controlled by ellipsometry and confirmed by Grazing Incidence X-Ray Diffraction measurements. Moreover, this signal has been simulated allowing the parameters extraction like the mean trench depth and periodicity of nanopatterned surface confirming the preceding measurements. The interest of 20 nm periodicity nanopatterned surfaces is demonstrated by Ge islands grown by Molecular Beam Epitaxy at 650°C and metal (Au, Ni) dots deposited by e-beam evaporation at room temperature. These self-assembled materials at the top of the pattern are studied by SEM and the accurately ordered gold nanoparticles are currently under way to study plasmon resonances. Thus, this study shows the interest of nanopatterned surface obtained by direct twist wafer bonding and selective thinning to self-organize laterally nanostructures with a simultaneous control of the size, density and positioning. ¹M. Bruel, Electron. Lett., 31, 1201(1995). ²F. Fournel, H. Moriceau, et al., Appl. Phys. Lett., 80, 793-795 (2002). ³R. A. Wind, M. J. Murtagh, et al., Appl. Phys. Lett., 78, 2205 (2001). ⁴A. Pascale, J. Eymery, et al., Surf. Sci., 600, 3187-3193 (2006). ⁵F. Leroy, J. Eymery, et al., Surf. Sci., 545, 211-219 (2003).

9:40 AM

L5, UHV-Bonding of Si/GaAs p-n Heterojunction Using Hydrogen Ion Beam Surfaces Cleaning: *N. Razek¹; A. Schindler¹; ¹Leibniz-IOM-Leipzig*

For applications of this bonding technique in MOEMS technology the bonding of AlInBv and Si is very interesting. We performed a study of GaAs to-Si bonding under UHV conditions. The wafers were cleaned using low energy (<500eV) hydrogen ion beam bombardment at low temperatures (<300°C) in order to remove the oxygen and carbon contaminant from a surface. The H-ion beam produce contamination free surfaces without changes in surface composition (stoichiometry) and surface roughness. The wafers were brought into contact at room temperature after cleaning under ultra-high vacuum (UHV), and bonded over the whole area without application of external mechanical pressure. High-resolution transmission electron microscopy images reveal that the wafers have been directly bonded without damage of the crystal lattice or intermediate layer and the interface is smooth. Current-voltage characterization shows near-ideal forward characteristics and the recombination in p-n heterojunction of Si/GaAs space charge region.

10:00 AM Break

10:20 AM Student

L6, Back-Channel Passivated Amorphous Silicon TFTs Fabricated at 300°C on a Clear Plastic Substrate: *Kunigunde Cherenack¹; Alex Kattamis¹; Bahman Hekmatshoar¹; James Sturm¹; Sigurd Wagner¹; I-Chun Cheng¹; ¹Princeton University*

We have fabricated back-channel passivated amorphous silicon thin-film transistors (a-Si:H TFTs) at 300°C on a free-standing optically clear plastic substrate. Back-channel passivated TFTs are less sensitive to environmental degradation, and are protected from damage from plasma etching used in various photolithography steps. This is the highest temperature that back-channel passivated a-Si:H TFTs have been fabricated on a plastic substrate. Our motivation for pushing the process temperature to 300°C is that the quality and stability of a-Si:H TFTs and therefore active matrix backplanes improves with increasing processing temperature. Mechanical stress in the device films is a critical variable during the fabrication of TFTs on plastic foil substrates. It is important to maintain the total stress in the device films below a critical value to prevent cracking and delamination, which lead to device failure. The total strain of the various layers also affects the dimension of the workpiece which can result in misalignment between various mask levels – especially between the gate level and the source/drain contact level in non-self aligned TFTs. Our back-channel process has been optimized to reduce this misalignment. We adjust the built-in stress in the device films by varying the film deposition conditions, e.g. plasma power.¹ The electrical performance of our devices fabricated at 300°C is equivalent to the performance of the same devices fabricated on glass at 300°C. We discuss the substrate preparation, TFT fabrication, electrical and bias-stress stability measurements. We gratefully acknowledge E.I. DuPont de Nemours for supporting this research and for providing substrate materials. This project is sponsored by the US Display Consortium. ¹Long, K.; Kattamis, A.Z.; Cheng, I.-C.; Gleskova, H.; Wagner, S.; Sturm, J.C., "Stability of amorphous-silicon TFTs deposited on clear plastic substrates at 250°C to 280°C," IEEE Electron Device Letters, vol.27, no.2, pp. 111- 113, Feb. 2006. ²Cheng, I.-C.; Kattamis, A.Z.; Long, K.; Wagner, S.; Sturm, J.C., "Stress Control for overlay registration in a-Si:H TFTs on flexible organic-polymer-foil substrates", Journal of the SID 13/7, 2005.

10:40 AM

L7, Flexible Polymeric and a-Si:H-Based Image Sensors Fabricated by Digital Lithography: *William Wong¹; TseNga Ng¹; Michael Chabinyk¹; Rene Lujan¹; Sanjiv Sambandan¹; ¹Palo Alto Research Center*

Conventional methods of monolithic integration, such as photolithography and vacuum deposition, are reaching a practical limit for large-area electronics. Processing areas will expand beyond the current 2m × 2m dimensions, with conventional fabrication of these large-area systems becoming increasingly complex. In order to reduce cost and complexity, the integration of inexpensive flexible substrates with organic and inorganic semiconductors will become necessary. In order to address this problem, a novel approach combining jet-printed lithography to fabricate flexible polymeric image sensors on a-Si:H-based backplanes will be presented. a-Si:H-based thin-film transistor (TFT) array backplanes were fabricated using jet-printed, digital lithographic processing on polyethylene naphthalate substrates with a maximum process temperature of 150°C. Two types of image sensors were integrated onto the flexible backplane. In the first case, a low-temperature a-Si:H p-i-n sensor layer was integrated onto the flexible 75 dpi resolution, 180×180 pixel array. The sensor layer possessed a linear light response with a measured quantum efficiency of ~ 70% at 488 nm with a dark current of 0.1 nA/mm² at a reverse bias voltage of 2V. In comparison, an organic photosensitive material having a transparent hole-transporting layer of tetraphenyldiamine was spun cast on top flexible a-Si:H TFT array. The sensor layer had a quantum efficiency of ~1% at 488 nm and a dark current of 1.1 pA/mm². Sensor properties on flexible platforms such as sensitivity, spectral response, and spatial resolution will be presented and compared to those on conventional substrates.

11:00 AM Student

L8, Amorphous Silicon Thin-Film Transistor Backplanes Deposited at High Temperature on Clear Plastic for Electrophoretic Displays: *Alex Kattamis*¹; Bahman Hekmatshoar¹; Kunigunde Cherenack¹; I-Chun Cheng¹; James Sturm¹; Sigurd Wagner¹; Sameer Venugopal²; Daniel Toy²; Douglas Loy²; Shawn O'Rourke²; David Allee²; ¹Princeton University, Department of Electrical Engineering; ²Arizona State University, Flexible Display Center

We fabricated active-matrix, amorphous silicon thin-film transistors (a-Si:H TFT) backplanes, on clear plastic substrates. The backplanes were made using a deposition temperature of 250°C and were used to drive electrophoretic (EP) frontplanes. Flexible a-Si:H TFT backplanes on a clear plastic substrates are desirable for drop-in replacements of a-Si:H TFT backplanes on glass. Initially research on a-Si:H backplanes on plastic involved reducing the deposition temperature to below the glass temperature (T_g) of common plastics such as polyethylene terephthalate (PET, $T_g = 78^\circ\text{C}$) and polyethylene naphthalate (PEN, $T_g = 120^\circ\text{C}$). While the initial performance of the TFTs made at $\sim 150^\circ\text{C}$ was acceptable it has become clear that for adequate long-term threshold voltage stability the a-Si:H TFT stack, especially the silicon nitride (SiN_x) gate dielectric, must be deposited at high temperatures. Recent results show that by increasing the deposition temperature of the gate dielectric SiN_x from 150°C to 250°C , the threshold voltage stability under constant gate bias stress, can be improved by 5x.¹ TFTs made at 350°C are the industrial standard and the most stable.³ Therefore a high-temperature clear plastic is the crucial enabler for such a process. We made pixel arrays of 8×8 and 32×32 with areas of $500\mu\text{m} \times 500\mu\text{m}$.² Each pixel consisted of one TFT with $W/L=70\mu\text{m}/5\mu\text{m}$ and a 3pF capacitor. The TFTs had threshold voltages of $\sim 4\text{V}$, mobilities of $0.5\text{cm}^2/\text{Vs}$, ON-OFF current ratios of $> 1 \times 10^7$, and OFF currents of $\sim 1\text{pA}$. The stability of the TFTs under constant gate bias stress was measured at room temperature by grounding source and drain, and biasing the gate at fixed voltages from 3V to 40V. Timing data was measured to ensure proper active-matrix functionality. Pulse widths for SELECT and DATA lines were 16 μs and 26 μs respectively with a frame time of 16ms were used. The pixel circuit maintains the storage node voltage over the 16ms frame time to within 200mV for 30V DATA line. The uniformity and yield of the backplanes $\sim 80\%$, was demonstrated with a laminated EP film. This result highlights the appeal of high temperature processing on plastics and is a step towards the replacement of glass by plastic foils. ¹K. Long, A. Z. Kattamis, I-C. Cheng, H. Gleskova, S. Wagner, and J. C. Sturm. IEEE Elec. Dev. Lett., 27 p. 111, 2006. ²A. Z. Kattamis, I-Chun Cheng, Ke Long, Bahman Hekmatshoar, Kunigunde Cherenack, Sigurd Wagner, James C. Sturm, Sameer Venugopal, Douglas E. Loy, Shawn M. O'Rourke, and David R. Allee. IEEE Journal of Display Technology, 2006, in press. ³F. R. Libsch and J. Kanicki, "Bias-Stress-Induced Stretched-Exponential Time Dependence of Charge Injection and Trapping in Amorphous Silicon Thin-Film Transistors." Appl. Phys. Lett., 62 p. 1286, 1993.

11:20 AM Student

L9, Indium Gallium Zinc Oxide as a Channel Material for Transparent Thin Film Transistors: *Arun Suresh*¹; Patrick Wellenius¹; John Muth¹; ¹North Carolina State University

There is increasing interest in single crystal and amorphous oxide semiconductors for a wide variety of applications including transparent and flexible transistors.^{1,2} These wide band gap semiconductors are not only transparent throughout the visible and near infrared but also have mobilities in the 10-50 $\text{cm}^2/\text{V}\cdot\text{sec}$ range. The amorphous nature of these materials and the ability to deposit them at room temperature also allow them to be deposited on flexible substrates. This is over an order of magnitude improvement compared to conventional amorphous thin films such as hydrogenated amorphous silicon and organic semiconductors that typically have electron mobilities of less than 1 $\text{cm}^2/\text{V}\cdot\text{sec}$. In this presentation we demonstrate the use of room temperature deposition of indium gallium zinc oxide (IGZO) deposited by pulsed laser deposition (PLD) as a channel material for transparent thin film transistors (TTFTs). Highly transparent devices with good electrical characteristics have been achieved. With a voltage threshold of 2 Volts, off currents of 10 picoamps, mobilities of 11 to 15 $\text{cm}^2/\text{V}\cdot\text{sec}$ and on/off ratios of 5×10^7 . The key role played by the PLD deposition conditions in realizing optimal transistor behavior is discussed. The role of the InGaZnO composition of the channel layer, the use of transparent conducting contacts as compared to metal contacts and the choice of gate

dielectric to optimize the electrical characteristics are also explored. ¹J. F. Wager, "Transparent electronics," Science, vol. 300, pp. 1245-1246, 2003. ²K. Nomura, H. Ohta, K. Ueda, T. Kamiya, M. Hirano, and H. Hosono, "Thin-film transistor fabricated in single-crystalline transparent oxide semiconductor," Science, vol. 300, pp. 1269-1272, 2003. ³K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, and H. Hosono, "Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors," Nature, vol. 432, pp. 488-492, 2004.

11:40 AM

L10, Late News

Session M: Oxide Thin Film Integration I

Thursday AM
June 21, 2007

Room: 129
Location: DeBartolo Hall

Session Chairs: Patrick Lenahan, Pennsylvania State University; Peter Moran, Michigan Technological University

8:20 AM Student

M1, Atomic Layer Deposition of Al_2O_3 and HfO_2 Gate Dielectrics on GaAs for MOSFET Applications: *Davood Shahrjerdi*¹; Tarik Akyol¹; Michael Oye¹; Ganesh Balakrishnan²; Arezou Khoshakhlagh²; Emanuel Tutuc¹; Diana Huffaker²; Sanjay Banerjee¹; ¹University of Texas at Austin; ²University of New Mexico

Recently, GaAs-based structures have attracted a lot of interests in complementary metal-oxide-semiconductor (CMOS) technology due to their inherently higher electron mobility than that of silicon. The lack of a high-quality native dielectric layer analogous to that of Si has been the overriding impediment to GaAs MOSFET technology. Nevertheless, as a non-native dielectric, the use of advanced high-k materials on GaAs is being extensively investigated in order to enable the fabrication of enhancement-mode MOSFETs. In this paper, we investigate the composition and structure of hafnium oxide and aluminum oxide grown on GaAs by atomic layer deposition (ALD). Furthermore, we study capacitance-voltage (C-V) behavior of GaAs MOS capacitors with and without using a thin Ge interfacial layer (IL) between GaAs and high-k dielectric. The first set of samples consists of 250nm thick n- and p-type GaAs epi layers grown on n+ and p+ GaAs substrates, respectively. Subsequently, the GaAs layers were terminated by a 15Å MBE-grown a-Ge at 400°C . The second set of samples was chemically treated to provide a hydroxylated surface. Hafnium oxide and aluminum oxide films were deposited on both sample batches using Tetrakis(dimethylamido)hafnium(IV) and Trimethylaluminum precursors, respectively, in a commercial SAVANNAHTM200 ALD reactor. The MOSCAP fabrication was finished by TaN metal gate deposition and patterning using a standard lithography and reactive ion etching of TaN in CF4 plasma ambient. X-ray Reflectivity (XRR) analysis and ellipsometry were carried out to determine the thickness of the grown Ge and high-k dielectric layers. X-ray photoelectron spectroscopy (XPS) corroborates the deposition of near-stoichiometric high-k layers. Cross-sectional TEM was carried out to study the gate stack structures, illustrating a thin GeOx layer between HfO_2 and Ge IL. The as-deposited samples with Ge IL and HfO_2 demonstrate a hysteresis of 270mV under bidirectional C-V sweeps performed at 1MHz. The frequency dispersion of these samples was improved upon annealing in forming gas ambient. On the other hand, the as-deposited Al_2O_3 directly on GaAs exhibits a hysteresis of 300mV, measured at 1MHz. In addition, for this set of samples we have observed that the flat-band voltage shifts at different small signal frequencies, whereas the accumulation capacitance appears to be unchanged. However, annealing in an O_2 ambient at $550\text{-}600^\circ\text{C}$ appears to mitigate hysteresis and frequency dispersion. In summary, we have studied the material properties and electrical characteristics of the ALD-deposited Al_2O_3 and HfO_2 on GaAs layers with and without utilizing an IL layer. MOSFET fabrication is underway.

8:40 AM Student

M2, Capacitance-Voltage Characterization on GaAs p- and n-MOS Devices with ALD HfO₂/Al₂O₃ Laminates as Gate Dielectrics: Tian Yang¹; Yi Xuan¹; Tian Shen¹; Peide Ye¹; ¹Purdue University

GaAs is a promising channel material for future high-performance CMOS devices due to its high intrinsic electron mobility. However, the lack of a high-quality, thermodynamically stable gate dielectric on GaAs has stymied every effort to employ this high mobility material in digital applications. Using the ALD technique developed in high-k/Si research community, we have successfully integrated ALD Al₂O₃ on GaAs and demonstrated some functional GaAs MOS-devices.¹ However, a direct ALD HfO₂, the most promising high-k candidate for Si CMOS with higher dielectric constant than Al₂O₃, on GaAs showed poor interface quality.² Recently, Si²⁻³ or AlN⁴ surface passivation before HfO₂ deposition was proposed. Si interfacial layer could alter the doping concentration of the GaAs channel after high-temperature process. The intrinsic thickness of AlN layer increases the effective oxide thickness (EOT), leading to difficulties of device scaling down. We present a systematic C-V study, for the first time, on ALD HfO₂/Al₂O₃ laminate gate dielectric n- and p- GaAs MOS devices. Using NH₄OH based surface pretreatment, 8 nm ALD Al₂O₃/HfO₂ laminate was deposited at 300°C. 8nm ALD HfO₂ was also deposited on GaAs substrate with the same doping concentration as control samples. Post deposition annealing was then conducted at 500°C by RTA in N₂ ambient, followed by Ni/Au gate evaporation. The RTA process has significantly optimized the HfAlO laminate C-V characteristics. The middle bandgap interface trap density (Dit) is ~2X10E11/cm²-eV determined by Terman method. Compared with ALD Al₂O₃ on GaAs¹ or AlN surface passivation before ALD HfO₂,⁴ the HfO₂/Al₂O₃ laminate dielectric shows higher dielectric constant (~10.5) with smaller EOT, which is less than 3nm. The accumulation capacitance is increased by almost 50% compare to ALD Al₂O₃ devices of the same oxide thickness for both n- and p-type GaAs substrate. The C-V curves show sharp transition from depletion region to accumulation region with improved hysteresis compared to direct ALD HfO₂. The 1KHz-1MHz frequency dispersion is less than 5% per decade for nMOS. The temperature dependent C-V measurements were also conducted on these samples by systematically varying both temperatures and frequencies. As temperature is increased from 300K to 500K, minority carriers begin to follow up the ac frequency. Inversion or low-frequency C-V curve can be observed for laminate gate dielectric on both n- and p-GaAs substrate, while with direct ALD HfO₂ or Al₂O₃ gate dielectric, only nMOS shows clear inversion C-V curve. More detailed analysis is on going. ¹P.D. Ye, et al., Applied Physics Letters 83, pp.180-182 (2003). ²S. Koveshnikov, et al., Applied Physics Letters 88 (2006). ³I. Ok, et al., IEDM Tech Dig., (2006). ⁴F. Gao, et al., IEDM Tech. Dig., (2006).

9:00 AM Student

M3, Observation of Near Interface Trapping Centers in Stressed Metal Gate Hafnium Oxide Field Effect Transistors Using Spin Dependent Recombination: Corey Cochrane¹; Patrick Lenahan¹; Jason Campbell¹; Gennadi Bersuker²; Arnost Neugroschel³; ¹Pennsylvania State University; ²SEMATECH; ³University of Florida

Although great progress has recently been made in the development of HfO₂ based metal oxide field effect transistor (MOSFET) technology, very little is known about the reliability problems associated with this new materials technology. One of the most vexing problems of conventional Si/SiO₂ and SiO₂/nitrided oxide MOS devices is the negative bias temperature instability (NBTI) which causes reduced drain current and shifts in threshold voltage when pMOSFETs are subjected to modest negative gate bias, typically at an elevated temperature. NBTI may also be a serious problem in new HfO₂ based MOSFETs. We combine conventional MOS gated diode measurements and very sensitive electrically detected electron spin resonance (ESR) measurements to detect and identify NBTI generated defect centers in fully processed HfO₂ pMOS field effect transistors (pMOSFETs). These HfO₂ based MOSFETs have an equivalent oxide thickness of slightly greater than one nm. The spectra of short term stressed devices were found to be significantly different from those spectra generated by the long term stressed devices. Not only do these spectra differ in g value, but also in width. Apparently two different defects are generated in short and long stressing periods. Neither of these spectra resemble those of NBTI generated

spectra in conventional Si/SiO₂ based devices. However, the long term NBTI generated defect spectra are somewhat similar to those observed in plasma nitrided oxide Si/SiO₂ based devices in that the g values g (HfO₂) = 2.0026 and g (nitrided SiO₂) = 2.0020 are virtually identical. Both the short and long term NBTI generated "interface" trapping defects, of the HfO₂ devices, are almost certainly not located precisely at the Si/dielectric boundary but slightly beyond it in the SiO₂ interfacial layer. The breadth and g values of the lines suggest that the defects may consist of oxygen deficient silicons bonded to oxygens, and involving some interaction with hafnium atoms.

9:20 AM Student

M4, Fluorine Incorporation at HfO₂/SiO₂ Interfaces in High-k Metal-Oxide-Semiconductor Gate Stacks: Jeong-Hee Ha¹; Kang-ill Seo¹; Krishna Saraswat¹; Paul McIntyre¹; Kyeongjae (KJ) Cho²; ¹Stanford University; ²University of Texas at Dallas

In recent years, silicon semiconductor devices have been dramatically scaled down to sub-100 nm MOSFET channel lengths in order to achieve higher device density and performance. In this regime, high-k dielectrics which can give large gate capacitances with dielectric films that are physically thicker than corresponding silicon oxide or oxynitride gate dielectrics are needed to reduce the substantial gate leakage current resulting from direct quantum mechanical tunneling across the dielectric layer. Recently, research on materials selection for alternative gate stack has converged on HfO₂ based high-k oxides (HfO₂, HfSiO₄, or HfSiON) deposited in a process which results in controlled formation of an ultra-thin SiO₂-like passivation layer on the Si (100) surface. This SiO₂-based interface layer provides the advantages of relatively low defect density and possible hydrogen passivation of dangling bonds afforded by the Si/SiO₂ interface. However, it has been reported that defects at the internal dielectric interface between HfO₂ and SiO₂ may produce fixed charge and threshold voltage instability under bias. In this presentation, we explore the possibility of passivating such defects by fluorine incorporation, using both computational and experimental analyses. Both ab-initio simulations and electrical measurements show that highly electronegative F atoms are able to remove midgap states that provide positive fixed charge, an intrinsic defect feature of HfO₂/SiO₂ gate stacks. Our results also indicate F incorporation increases the leakage current if an excessive amount of F is incorporated in the dielectric films after passivating under-coordinated Hf ions at HfO₂/SiO₂ interface. However, considering the passivating ability of F ions for under-coordinated Hf ions at this interface and the strength of their bonding, a fluorination process is advantageous for improving the reliability of high-k gate stacks. Approaches to maximize the advantages of F incorporation in high-k gate stacks are also discussed.

9:40 AM

M5, Studies on Oxygen Conduction in Rare-Earth Doped Hafnia and Relationship to Electrical Transport Properties: Siddarth Krishnan¹; Paul Kirsch¹; Annamalai Karthikeyan²; Shriram Ramanathan²; ¹International Sematech; ²Harvard University

Stabilization of crystalline phases in ceramics at low temperatures has traditionally been explored by alio-valent doping. Adapting such approaches in the area of alternate gate dielectrics can possibly enable synthesis of oxide thin films with superior dielectric constant compared to un-doped counterparts. Potential issues with such approaches include creation of oxygen vacancies due to charge neutrality considerations. The presence of oxygen vacancies may lead to altered leakage currents and trap levels. Also, it may lead to increased interfacial oxide growth due to rapid oxygen diffusion through the vacancies. Therefore it is essential to perform systematic research on doped-oxides to investigate their dielectric properties and performance as gate stack materials. Rare-earth doped hafnia thin films have been synthesized by physical vapor deposition followed by oxidation. Systematic studies have been done to vary the doping levels by controlling the deposition rates. Electrical measurements have been carried out on various oxide films by fabricating capacitor structures. Oxygen transport has been investigated in detail on the various samples using a custom-built high temperature electrochemical probe station. Oxygen-ion conductivity studies have been performed as a function of temperature up to nearly 1000°C. We have found that rare earth doping (e.g. with Sc) of hafnium oxide reduces leakage current by several orders of magnitude compared with pure hafnium oxide. The keys to reducing the leakage current and equivalent oxide thickness (EOT) are

stabilization of the higher dielectric constant tetragonal phase of HfO_2 and careful engineering of the interface between silicon and the high k material. An optimal doping level is necessary to maximize the dielectric constant. Metal-insulator-semiconductor capacitors (MISCAPs) with equivalent oxide thickness less than 2nm and leakage current density below $1 \times 10^{-8} \text{ A/cm}^2$ after high temperature annealing have been demonstrated. Oxygen-ion conductivity results show that upon suitable passivation of the doped-hafnia films, the conductivity can be manipulated to remain close to that of the pure oxides. The conductivity values will be compared with previous work on similar ceramic systems studied in bulk form. We will discuss these results in context of future prospects of gate stack scaling using crystalline oxides.

10:00 AM Break

10:20 AM Student

M6, Atomic Layer Deposition of HfO_2 on III-V Semiconductors: Effects of Surface Treatment and Post-Deposition Anneals: Eunji Kim¹; Po-Ta Chen¹; Donghun Choi¹; James Harris¹; Yoshio Nishi¹; Krishna Saraswati¹; Paul McIntyre¹; ¹Stanford University

III-V semiconductor-channel field effect transistors are receiving increased attention among research groups due to their potential for very high electron mobility and low power dissipation in nano-scale MOS devices. The native oxide of GaAs and InGaAs, however, exhibits poor passivating properties and a large density of defect states exists at the interface between the native oxide and III-V semiconductors. Therefore, it is essential to achieve a high quality interface between gate dielectrics and III-V channel materials by removing the native oxide on III-V surfaces prior to fabrication of high-performance MOS devices on these high-mobility channel materials. We have investigated the electrical and physical properties of W/ALD- HfO_2 /III-V (p & n-type GaAs, InGaAs) MOS capacitors with various surface treatments prior to HfO_2 atomic layer deposition and with post deposition anneals. X-ray photoelectron spectroscopy shows that non-treated III-V semiconductor surfaces have various oxide binding states associated with Ga_2O_3 , As_2O_3 , As_2O_5 . After sulphur passivation following native oxide removal by HCl etching, the surface is oxide-free and Ga-S bonding (Ga_2S_3) is observed. The physical thickness of the ALD- HfO_2 film investigated ranges from 18.3 nm for the initially non-treated substrate surface to 19.8 nm for the S-passivated, as determined from x-ray reflectivity data. After the samples were annealed at 450°C for 2min in N_2 ambient, a decrease in physical thickness and an increase in film density were confirmed by x-ray reflectivity. Electrical properties were studied by capacitance-voltage and current-voltage measurements on MOS capacitors. The S-passivated samples show improved electrical properties compared to non-treated samples, as indicated by the decrease in CV hysteresis, recovery of a near-ideal flat band voltage, and complete elimination of frequency dispersion of the capacitance, without sacrificing gate capacitance. Post-deposition anneals seem to improve electrical properties of the gate stack depending on the annealing conditions. The measured CV curve of the annealed samples is less stretched out, the accumulation capacitance increases, and flat-band voltage is shifted back to the ideal flat band voltage, while the gate leakage current is suppressed.

10:40 AM Student

M7, Electrical Properties of Thermally Grown $\text{TiO}_2/\text{SiO}_2$ Stack MIM Capacitors: Bing Miao¹; Rajat Mahapatra¹; Alton Horsfall¹; Nick Wright¹; ¹Newcastle University

The low energy density in conventional capacitors severely limits attempts to miniaturize power electronics and imposes severe design limitations. The key to achieve high energy density is by utilising a dielectric layer that can support a high electric field strength. We use high-K dielectrics grown by thermal oxidation to form capacitors based on a $\text{SiO}_2/\text{TiO}_2$ stack, fabricated using thermal oxidation. TiO_2 and SiO_2 films are evaluated in stacked structures between degenerately doped Si bottom and Al top electrode. TiO_2 films were grown by thermal oxidation from Ti in an oxygen ambient at 500, 600, 700, 800°C respectively. The lowest leakage current was obtained at the oxidation temperature of 600°C, whilst the changes in capacitance are negligible. And we consider this to be optimum. We have fabricated $\text{TiO}_2/\text{SiO}_2$ MIM capacitors with 100nm and 40nm SiO_2 thickness with a fixed 100nm TiO_2 thickness by thermal oxidation of a 50nm thick Ti layer at 600°C. The highest effective dielectric constant of $\text{TiO}_2/\text{SiO}_2$ films is 45, which is over 11 times

that of silicon dioxide. The voltage linearity coefficient (VCC) is an essential parameter for high accuracy IC capacitor applications. VCC consists of the quadratic (α) and linear (β) voltage coefficients. The quadratic VCC (α) is linearly proportional to $1/t_{\text{ox}}$, and is expected to have a magnitude below 100ppm/V². SiO_2 MIM capacitors elucidate negative parabolic capacitance – voltage characteristics, whereas high-K MIM capacitors illustrate positive parabolic curves. Connecting these layers in series, the voltage across the stack is divided between these two dielectrics, according to the dielectric constants of the constituent layers. The compensation effect from the use of the stack structure is observed by changes in the extracted VCC. The lowest VCC value of -6 ppm/V² was obtained with the SiO_2 layer thickness of 100nm. In contrast, the capacitor with the thinner SiO_2 layer showed a reduction in VCC to -20 ppm/V². The VCC variation of the stack dielectrics is caused by the change in the properties of the SiO_2 layers beneath TiO_2 layers, which have a reduced VCC as the SiO_2 thickness reduces. The reduction of thickness layer also plays a critical role in leakage current at low bias by suppressing the trap assisted conduction current through the stack. Both capacitors can satisfy the leakage requirement for MIM capacitor specified in the ITRS at voltage under 2.4V. We present results demonstrating that MIM capacitors formed from a thermally oxidized $\text{TiO}_2/\text{SiO}_2$ stack has a VCC of -20 ppm/V² and capacitance density of 2.83fF/ μm^2 can be engineered, with an operational voltage in excess of 20V, which exceeds the 2007 ITRS target value. Further increase in the capacitance density may be achieved by reducing TiO_2 thickness, whilst maintaining the device characteristics.

11:00 AM Student

M8, Electron Spin Resonance Studies of Silicon Nano-Crystal Flash Memory Devices: Jason Ryan¹; P. Lenahan¹; L. Vishnubhotla²; S. Straub²; M. Ramachandran²; R. Rao²; T. Merchant²; ¹Pennsylvania State University; ²Freescale Semiconductor

As the fundamental physical limits of conventional Flash memory are approached, new charge storage structures must be explored. Conventional Flash memory devices suffer from stress induced leakage currents (SILC) caused by trap assisted tunneling which results in a reduction of data retention time. The continued scaling of Flash devices exacerbated this problem. A promising potential solution to this problem is the use of very small Si-nano-crystals. In theory, Si-nano-crystal Flash memory could reduce or eliminate the reliability problems associated with trap assisted tunneling because the tunneling process clearly involves highly localized tunneling current paths. The introduction of nano-crystals will clearly help with the SILC problems involving the dielectric between the Si-channel and the nano-crystals (tunnel oxide), but the open spaces between the nano-crystals may lead to new problems. In a nano-crystal device, oxides “above” the nano-crystal layer (interlayer oxide) are exposed to charge carriers. In this study, we utilize electron spin resonance (ESR) measurements on $\text{SiO}_2/\text{Si-nano-crystal}/\text{SiO}_2$ structures to explore the interaction of charge carriers and oxide defects in these systems. To simulate device operation, ESR measurements were made before and after the structures were subjected to electron and hole flooding. The densities of several intrinsic paramagnetic defects (most importantly, E' centers) are greatly altered by the electron or hole flooding. Various post-deposition treatments quite significantly reduce or enhance the generation of these paramagnetic defects. We find a strong, but imperfect, correlation between E' center generation and oxide leakage current. Preliminary results also suggest that, at least for the electron flooding case, the generated E' centers are electrically neutral. An additional interesting observation is that our results also indicate that there are far lower densities of silicon/silicon dioxide interface defects (Pb centers) located at the Si-nano-crystal/ SiO_2 interface than at the Si-channel/ SiO_2 interface. This surprising result may provide insight into the underlying physical mechanisms involved in interface trap generation.

11:20 AM

M9, Depth-Resolved Cathodoluminescence Spectroscopy Study of Defects in SrTiO_3 : Jun Zhang¹; Shawn Walsh¹; Charles Brooks²; Darrell Schlom²; Mary Zvanut³; Leonard Brillson¹; ¹Ohio State University; ²Pennsylvania State University; ³University of Alabama at Birmingham

SrTiO_3 is a technologically important material with a variety of electrical behaviors, from a high dielectric constant paraelectric, to a ferroelectric induced by epitaxial strains, and to a semiconductor or even metallic

superconductor if suitably doped. It has wide applications in tunable dielectric devices, dynamic random access memory and as a gate oxide in transistors, and it is also a perfect substrate for epitaxial perovskite oxides. The broad range of physical properties and applications of SrTiO₃ make it very important to investigate its electronic defects, which may limit the material multifunctionality, efficiency and loss. In this presentation, we report depth-resolved cathodoluminescence spectroscopy (DRCLS) study of defects in SrTiO₃ single crystals and epilayers, with special attention paid to defect distributions and their dependence on annealing. DRCLS measurements were performed in an ultrahigh vacuum chamber with samples cooled with a helium cryotip to ~ 42 K for all samples. Incident beam current was held constant at 2 mA so that power increases with increasing beam voltage, and depth-dependent cathodoluminescence (CL) spectra were collected. The samples studied are SrTiO₃ epilayers grown on SrTiO₃ substrates by molecular beam epitaxy technique and SrTiO₃ single crystals from different vendors in the forms of as-received and annealed. For the single crystal substrates, the CL spectra are dominated by features that are intrinsic to SrTiO₃, including a band gap peak at 3.2-3.3 eV, a broad peak around 4.2 eV related to interband transition and a peak at 2.4 to 2.5 eV due to self-trapped excitons. Defect related CL features are characterized by peaks around 1.6 eV and 2.2 eV, corresponding to Ti interstitial and O vacancy (V_O), respectively, and the concentrations of such defects depend on the specific vendors, and hence the growth conditions, of the SrTiO₃ single crystals. Ti interstitials are identified in the bulk but are absent in the near-surface region, while more O vacancies are found near the surface, and oxygen annealing removes O vacancies within 50 nm of the surface. Moreover, electron paramagnetic resonance (EPR) study indicates the existence of Fe³⁺-V_O defect complex in SrTiO₃ single crystals, and the concentration of such a defect complex also depends on annealing. In SrTiO₃ epilayers, more Ti interstitials and oxygen vacancies are found in thinner epilayers, and interface-specific defects were found only in the 50 nm thick epilayer, but not in the 100 nm thick one, suggesting higher crystal quality for the thicker film. Our results reveal a strong dependence of defects and their depth distributions in SrTiO₃ on the crystal growth and processing and provide insights on optimizing the electrical properties of SrTiO₃ through controlling crystal growth and processing conditions.

11:40 AM

M10, Improved Cell Performance of NO-Based Storage Dielectric by N₂O Treated Nitride Film for Trench DRAM: *Chih-Ming Chang*¹; Yung-Hsien Wu¹; Chien-Kang Kao²; Chun-Yao Wang¹; Chia-Ming Kuo²; Alex Ku²; Tensor Huang²; ¹National Tsing Hua University/ProMOS Technology Inc.; ²ProMOS Technology Inc.

To meet the requirement of the growing sophisticatedly memory-hungry applications, the DRAM chip capacity is multiplied for past years. One enormous challenge the DRAM makers confronted with is how to construct high density DRAM in a reasonably sized chip area since it is difficult to maintain sufficient charge in the ever-shrinking cell capacitor while keeping acceptable retention time. Although high-k material is an unavoidable candidate for storage dielectric to enhance cell capacitance, it is always implemented in the 12-inch fab because of cost concern. In this work, a new process is proposed for 8-inch fab to enhance the cell performance of existent NO (nitride/oxide)-based storage dielectric. Conventional NO storage dielectric was formed by the following four major steps. (1) in-situ nitridation in ammonia (2) LPCVD nitride deposition. (3) wet oxidation of the nitride film. (4) final ammonia nitridation. For NO dielectric, the tunneling current and intrinsic breakdown issues resulted from charge trapping in the nitride film hamper further scaling. To further enhance the nitride quality of NO dielectric, other two dielectrics were investigated. Samples denoted as N₂O_1 were performed by the insertion of N₂O anneal process between step (1) and (2) while those denoted as N₂O_2 were prepared by the same process condition as N₂O_1 with additional N₂O anneal between step (2) and (3). XPS analysis was used to study the bond structure in the nitride film. The NH₃ bond signal is significantly higher in the NO dielectric and it was greatly reduced with N₂O treatment. The less NH₃ bond implies less hydrogen content in the nitride and consequently curbs electron traps incorporated which is essential to improve the leakage current and reliability. The leakage current comparison reveals the strong dependence on NH₃ bond in the nitride layer. The NH₃ bond enhances the charge trapping in the NO dielectric and therefore deteriorates the leakage performance. For N₂O_1,

compared with NO dielectric, 30% leakage current improvement is achieved without compromising the cell capacitance and the result also indicates that under appropriate N₂O treatment the dielectric constant of nitride film would not be degraded. With these promising properties, the long-term reliability was evaluated by constant voltage stress and then transformed the stress voltage to operation voltage via linear E-model extrapolation. Not only is the reliability performance qualified with less than 438 ppm failure rate after 10-year operation, but the much better lifetime than NO dielectric is obtained in N₂O_1. In conclusion, with properly treated nitride film by N₂O, augmented cell performance can be realized in terms of leakage current, cell capacitance and reliability. The employment of conventional NO storage dielectric can be extended in the trench DRAM without extra tool investment, which is beneficial to 8-inch fab to fortify its competitive advantages.

Session N: Contacts to Wide Bandgap Semiconductors

Thursday AM
June 21, 2007

Room: 102
Location: DeBartolo Hall

Session Chairs: Huili (Grace) Xing, University of Notre Dame; Lisa Porter, Carnegie Mellon University

8:20 AM Student

N1, Correlation of Bulk Native Point Defects and Metal Reactivity on ZnO Using Depth Resolved Cathodoluminescence Spectroscopy: *Lee Mosbacher*¹; Sleiman El Hage¹; Michael Hetzer¹; David Look²; Leonard Brillson¹; ¹Ohio State University; ²Air Force Research Laboratory/MLPS

ZnO is an emerging semiconductor system for spintronic, nanoelectronic and optoelectronic devices. Important to realization of these devices is control of the metal-ZnO interface. We systematically investigated this interface on single crystals grown by different methods from several sources. Many authors report on mechanisms that can affect Schottky barrier formation at metal-ZnO interfaces. Adsorbates such as carbon and hydroxide can donate electrons and create a surface conductive layer that produces a quasi-Ohmic contact. Hydrogen, a shallow donor in ZnO, can increase carrier concentration and promote tunneling through thin barriers. Deep level native point defects can enable defect-assisted hopping through the barrier. Using a remote oxygen plasma, we have processed ZnO to identify the magnitude of each mechanism for Al, Au, Ir, Ni, Mo, Pd, Pt, and Ta contacts on ZnO. Depth-resolved cathodoluminescence spectroscopy (DRCLS) reveals the presence of 3 defects at energies of 2.1, 2.5 and 3.0 eV. These deep level states vary in concentration with vendor, with depth from the interface, and with metal contact. Current-voltage measurements illustrate that material containing high concentrations of defects in the subsurface strongly affect reverse currents, idealities and barrier heights acquired from current-voltage measurements. After annealing these contacts at temperatures of 350°C, 450°C, 550°C, and 650°C in an argon ambient, DRCLS spectra identifies defect formation that correlates to the nature of the metal-ZnO interface. Metals that form oxides show increased deep-level emissions that have been attributed to oxygen vacancies, while metals that form eutectics with Zn reveal increased luminescence from defects associated with Zn vacancies. Ta contacts annealed at 550°C create blocking contacts to ZnO, and DRCLS in the interface region reveal the formation of a Ta oxide. Al contacts also form blocking contacts at temperatures that depend on the native point defect densities. DRCLS of the subsurface and forming oxide reveal an increase in a 2.5eV transition often associated with oxygen vacancies. Au contacts that are annealed above the eutectic temperature for Au-Zn illustrate an increase of the 2.1eV defect level that correlates with Zn vacancy formation. Material variations not only occur between vendors, but also vary from different crystal batches. These differences in native point defect densities have a significant impact on defect formation at elevated and even room temperature. Samples containing high concentrations of native point defects can increase reactions at the subsurface, thus creating defects associated with the metal-ZnO surface chemistry. Overall we find that ZnO crystals containing high concentrations of native point defects near the surface lead

to pronounced increases in metal-ZnO reactivity and electrical changes at lower annealing temperatures. In general, low defect ZnO samples can create contacts with low reverse currents, ideality, high barrier heights, and increased thermal stability.

8:40 AM

N2, First-Principles Studies of Metal (111)/ZnO{0001} Interfaces: *Yufeng Dong*¹; Leonard Brillson¹; ¹Ohio State University

Metal/ZnO interfaces are central to all ZnO electronic device applications, yet their electronic properties have only recently been explored in detail. It has recently been shown that surface conditions and near-surface native defects can affect ZnO Schottky barrier heights (SBHs). However, these n-type barriers appear limited to 0.6–0.8 eV even after surface and subsurface defects of ZnO substrate are minimized e.g., by O₂/He plasma treatment.¹ Recent theories of metal adsorbates on ZnO(0001) surfaces describe preferred adsorption sites; however, the atomic and electronic structures of metals on the ZnO surfaces and their relation to the SBH remain unknown. Here we present first-principles calculations based on density functional theory (DFT) of model metal/ZnO interfaces using VASP with the projector augmented wave (PAW) method. The general gradient approximation with self-interaction corrections (GGA+U) was applied to widen the intrinsic-underestimated band gap of ZnO in GGA. The atomic and electronic structures for a variety of face-centered-cubic metals (Al, Au, Ag, Pt, and Pd) on the two basal planes of ZnO, O-terminated (000-1)-O and Zn-terminated (0001)-Zn surfaces, have been calculated. Several high-symmetry interface structures were considered: fcc hollow, hcp hollow, and on the top. For O-terminated (000-1)-O interface, interface metal atoms prefer to the on-top adsorption sites, which is the regular lattice site for the next Zn layer, while for Zn-terminated (0001)-Zn interface, the fcc hollow and hcp hollow positions are preferred. It was found that an electric field is present along the ZnO[0001] direction, which is rather uniform for Al-, Au, and Ag-ZnO interface supercell, while it is not for Pt- and Pd-ZnO interface supercells. This may be due to the strong polarization induced by the strained interface. SBHs were evaluated in the presence of the uniform electric field. The results show that SBHs at metal/ZnO interfaces are very sensitive to the specific interface chemical bonding. Interface metal-zinc bonds can give an interface Fermi level (Ef-i) near the conduction band edge of ZnO, while the contribution of metal-oxygen bonds depends on the specific metal. Using the calculated band gap, the SBHs for O- (Zr-) terminated Ag/ZnO, Au/ZnO, and Al/ZnO interfaces are 1.1 eV (-0.2 eV), 0.8 eV (-0.2 eV), and -0.6 eV (-0.4 eV) respectively. Interface simple metal-anion bond (e.g., Al-O) tends to give Ohmic contact while noble metal and oxygen bonding (e.g., Au-O or Ag-O) tends to pin Ef-i near mid-gap. Nonuniform electric fields prevent calculation of SBHs at Pt and Pd/ZnO interfaces, indicating that polarization inside the ZnO is strongly coupled to the surface or interface boundary conditions. These results emphasize the importance of interface chemical bonding on macroscopic metal/ZnO barriers that are likely to occur in conventional contact formation. ¹H. L. Mosbacker et al., Appl. Phys. Lett., in press.

9:00 AM Student

N3, Improvement of the Light Output of GaN-Based LEDs by Introducing ZnO Nanostructure: *Joon-Ho Oh*¹; Hyun-Gi Hong¹; Hyun-Seok Na¹; Kang-Won Kim¹; Tae-Yeon Seong¹; ¹Korea University

Highly efficient LEDs are of great importance for their potential application in back light units for LCD and general illumination. To realize such highly efficient devices, p-type ohmic contact layers with low specific contact resistivity and high transparency is crucial. In addition, an increase of light extraction efficiency is a crucial issue. External quantum efficiency is still very low as compared with internal quantum efficiency. One major reason is related to high refractive index (2.1–2.5 at 405 nm) of GaN-related materials and indium tin oxide (ITO) top contact layers, resulting in the escape cone with a small angle for the emitted light and so causing most of the light to experience total internal reflection. Thus, to enhance light extraction efficiency, several methods, such as laser lift-off, GaN surface-roughening, and contact layer patterning, were introduced. In particular, a contact layer patterning technique was found to be effective in improving light extraction by inducing photonic crystal effect or diffuse scattering. In this work, we introduced transparent conducting oxide (TCO) (such as ZnO) nanostructures on the p-type NiZn/ZnO electrodes. The surface patterning

method was shown to be very effective in forming nanostructures on the NiZn/ZnO. The NiZn/ZnO shows good ohmic behaviour when annealed at 450 and 550°C in air. Annealing the sample at N₂ ambient results in degradation. LEDs fabricated with the patterned electrodes give reasonable forward bias and so better light output as compared with LEDs without patterned electrodes. Ohmic mechanisms are described and discussed based on x-ray photoemission spectroscopy and x-ray diffraction results.

9:20 AM Student

N4, Non-Alloyed Ohmic Contact Using Selective-Area Growth by Plasma-Assisted Molecular Beam Epitaxy: *Huichan Seo*¹; Patrick Chapman¹; Philip Krein¹; Kyekyoon Kim¹; ¹University of Illinois at Urbana-Champaign

With the development of GaN-based materials for electronic and optoelectronic devices, the formation of low-resistance, thermally-stable ohmic contacts has been a critical issue for high-performance devices. Attempts to achieve low ohmic contact resistance have been under way by using Ti/Al, Ti/Al/Ti/Au and other metal alloys. However, during the annealing process, metals react with GaN resulting in formation of metal nitrides, which, in turn, cause critical reliability problem for high-temperature operation. To further facilitate higher performance gate length needs to be reduced. But, with metal alloys it is difficult to fabricate fine gate patterns between the source and the drain. To resolve these difficulties, non-alloyed metal contacts may be employed. To reduce the specific contact resistance for non-alloyed ohmic contacts, various surface treatments have been utilized including Ar sputtering, reactive ion etching, (NH₄)₂S_x treatment, and KrF excimer laser irradiation. These techniques, however, can give rise to physical and chemical damage on the surface of the other components, such as channel regions, which may degrade the device performance. To achieve low contact-resistance, we grew n+-GaN interlayer between the n-type GaN and the metal contacts under optimal conditions. This technique does not produce damages on the GaN surface of other components. Samples used in this study consisted of 200-nm-thick n-type GaN grown by PAMBE on an MOCVD-grown semi-insulating GaN-template. The electron concentration and mobility were 3.8 * 10¹⁷ cm⁻³ and 300 cm²/Vs, respectively. A 100-nm-thick patterned SiO₂ mask was formed on the n-GaN to facilitate the PAMBE-SAG process. After a 60-nm-thick n+-GaN layer was grown on SiO₂, poly-GaN and SiO₂ mask were removed by a molten KOH solution and alloyed ohmic metals of Ti, Ti/Al and Ti/Al/Ti/Au were deposited on n+-GaN for the transmission line method (TLM) measurement. In the I-V measurement of the metal pads with a gap spacing of 5 μm, the samples with SAG showed much higher current transportation than those without SAG, which suggests that a highly doped layer can effectively facilitate tunneling of the electrons on the GaN surface tunnel through the barrier between metals and GaN. The specific contact resistances of Ti, Ti/Al and Ti/Al/Ti/Au contact with SAG were 3.5 * 10⁻⁵, 5.1 * 10⁻⁵ ohm-cm² and 3.71 * 10⁻⁵ ohm-cm², respectively, demonstrating that the SAG technique can be gainfully applied to various kinds of metal contacts. The interface reaction between GaN and the metal contacts will be examined by X-ray photoemission spectroscopy (XPS) and secondary ion mass spectrometry (SIMS).

9:40 AM Student

N5, V- and Ti-Based Ohmic Contacts to Plasma-Etched n-Al_{0.58}Ga_{0.42}N: *Mary Miller*¹; B. H. Koo¹; Suzanne Mohney¹; Katherine Bogart²; ¹Pennsylvania State University; ²Sandia National Laboratories

Plasma-etching of AlN-rich Al_xGa_{1-x}N is required for fabrication of bottom-emitting UV-light emitting diodes. Plasma-etching removes layers to open up the contact window to the n-type material and enables both n- and p-type contacts to be made to the same side of the device. We have studied the metal/semiconductor interface of both Ti- and V-based ohmic contacts to AlN-rich Al_xGa_{1-x}N using transmission electron microscopy, and we have found significant differences in the phase formation and reaction depth of contacts made to as-received n-Al_{0.58}Ga_{0.42}N as compared to plasma-etched n-Al_{0.58}Ga_{0.42}N. For contacts to the plasma-etched n-Al_{0.58}Ga_{0.42}N, both V-based and Ti-based contacts exhibited extremely limited reaction with the semiconductor. This finding is contrary to our observations of annealed Ti-based contacts to n-Al_xGa_{1-x}N when the semiconductor is not etched. Instead of a deep reaction region, a thin layer of AlN was found at the interface of both metallizations. Previous work by our research group showed that in

order to optimize V/Al/V/Au contacts to plasma-etched n-Al_{0.58}Ga_{0.42}N, the thickness of the first V layer and annealing temperature had to be increased. With X-ray photoelectron spectroscopy studies, we also showed that the Al and N concentrations preferentially decreased and the oxygen concentration increased with etching. The formation of AlN at the metal/semiconductor interface may be a result of an increased thickness of oxide layer at the etched semiconductor surface, which limited reaction with the semiconductor. Since the specific contact resistance of the contacts to plasma-etched n-Al_{0.58}Ga_{0.42}N were minimized for these samples, the AlN must be beneficial to the ohmic contacts. There are two possible reasons why the AlN might help the formation of ohmic contacts. The first is that Al within the metallization may react with the etched n-Al_{0.58}Ga_{0.42}N to form AlN with concurrent formation of nitrogen vacancies in the semiconductor. Current transport by tunneling would therefore be increased. The second possibility is that the AlN in contact with the n-Al_{0.58}Ga_{0.42}N creates a two dimensional electron gas, which would increase the electron concentration at the interface. Further Ti-based ohmic contact optimization was also conducted. It was found that although V-based contacts provide lower specific contact resistance at lower temperatures for as-received n-Al_{0.58}Ga_{0.42}N, the Ti-based contacts provide similar resistances to the V-based contacts to plasma-etched n-Al_{0.58}Ga_{0.42}N. The reason why the resistances are similar for the plasma-etched material likely originates from the formation of AlN at both contact/semiconductor interfaces.

10:00 AM Break

10:20 AM Student

N6, Ohmic Behavior and Interfacial Reaction of Si/Ti/Al/Mo/Au Ohmic Contacts on AlGaIn/GaN High Electron Mobility Transistors: *Liang Wang*¹; Fithi Mohammed¹; Ilesanmi Adesida¹; ¹University of Illinois at Urbana-Champaign

Ti/Al/metal/Au metallizations are used as standard ohmic contacts for n-GaN and AlGaIn/GaN electronics such as high electron mobility transistors (HEMTs). Ti/Al/Mo/Au has demonstrated low contact resistance (R_c), sharp edge acuity, and excellent thermal stability. We have showed that during annealing Ti/Al/Mo/Au reacted with AlGaIn/GaN non-uniformly where TiN formed preferentially along dislocations. TiN islands penetrated through the AlGaIn layer, established intimate contact with 2DEG, and enabled direct transport of electrons. Si is an n-type dopant for GaN. It is hypothesized that Si can diffuse into the epilayers and form a highly-doped region when Si-containing metallizations are annealed. It is also proposed that silicides with low work-functions may form and enhance ohmic contact formation. Our investigations, however, have suggested that depending on Si thickness, when inserted between the Ti and Al layers, the preponderant observation was that Si engendered reactions within metallizations rather than doping GaN. The ohmic characteristics and the interfacial reactions of Ti/Si/Al/Mo/Au or Ti/Si/Al/Si/Mo/Au could be tailored by changing the amount of Si. It was also observed that when optimal amount of Si was used, low R_c were achieved over a larger processing window. Structurally discrete TiN island formation was suppressed; rather, thin AlN layers formed on AlGaIn when thick Si layers were utilized. Here, we report the ohmic characteristics and interfacial reactions of Si/Ti/Al/Mo/Au on AlGaIn/GaN. For the Si/Ti/Al/Mo/Au, three different Si thicknesses were used, namely, 1, 5, and 10 nm. R_c was extracted from L-TLM patterns. Minimal R_c of 0.41, 0.38, 0.31, 0.63 Ω-mm have been obtained for Si-less, 1 nm, 5 nm and 10 nm samples, respectively. These optimal performances were obtained at 850°C for Si-less, 1 nm, and 5 nm samples; while the 10 nm samples exhibited optimal R_c at 650°C. Similar to what was observed when Si was inserted between Ti and Al, low R_c is achievable with a wider temperature window. XTEM studies show that for the 1 nm sample, similar to the Si-less case, TiN islands formed along dislocations with a depth of ~ 100 nm into GaN. Si was found to dissolve in metals instead of forming silicide or doping GaN. Increasing Si thickness to 5 nm led to formation of both TiN islands and Au-Al-Si protrusions. Even more Si incorporation (10 nm) resulted in complete suppression of TiN formation; instead, Au-Al-Si formation took place along dislocations. Even for the 10 nm sample, no silicide formation was observed. We thus believe that enhancement of performance by Si is not due to the proposed silicide mechanism or Si-doping mechanism. Si tailors interfacial reactions by being involved in the metallurgical reactions within the metal layers.

10:40 AM Student

N7, Effects of Mo:Al Ratios on Mo/Al/Mo/Au Ohmic Contacts for GaN-Based HEMTs: *Anirban Basu*¹; Fithi Mohammed¹; Liang Wang¹; Vipin Kumar¹; Ilesanmi Adesida¹; ¹University of Illinois at Urbana-Champaign

GaN-based HEMTs have demonstrated remarkable performances in terms of output power, power-added efficiency and operating temperature which have made them versatile candidates for microwave power and low-noise applications. One of the factors in the realization of these high-performance devices is the continuous improvements in the ohmic contact technologies. The most widely utilized contact metallization schemes comprise of Ti/Al as the base with various overlayers, such as Ni/Au, Pt/Au, and Mo/Au, added to prevent surface oxidation of Al which is detrimental to the achievement of low-resistance ohmic contacts. Usually, these metallizations require annealing at temperatures above 750°C, which is higher than the melting point of Al (~660°C). Often such high temperatures result in considerable lateral flow due to the formation of viscous AlAu₄. Excessive lateral flow may lead to short-circuiting between the source and drain electrodes of HEMT devices. The high annealing temperature also precludes the fabrication of self-aligned T-gate GaN-HEMTs since the gate collapses due to reactions between the Ni/Au-gate-metal and the deposited Al in the ohmic contact. To develop ohmic metallizations that yield low contact resistances at temperatures well below the Al melting-point, a metallization scheme containing Mo/Al/Mo/Au has been developed. Mo is an excellent refractory metal with a high melting point which demonstrates near-linear I-V characteristic on n-GaN. Moreover, the solubility of Au in Mo is relatively low. For a consistent realization of low-resistance ohmic contacts, an investigation of optimum Mo:Al thickness ratios and the corresponding annealing temperatures are required. In this work, we report on our investigations of the ohmic contact characteristics of Mo/Al/Mo/Au metallization on an Al_{0.3}Ga_{0.7}N/GaN heterostructure at temperatures ranging from 350°C to 650°C for different Mo:Al ratios. To check for consistency of performance, identical investigations were carried out on different AlGaIn/GaN HEMT layers. Electron beam and thermal evaporations of Mo/Al/Mo/Au were performed for a total thickness of 100 nm on each of four epitaxial samples and with four different Mo:Al ratio of 1:2, 1:3, 1:4 and 1:5, respectively. The investigations show that for annealing temperatures below 450°C the annealed metallizations displayed Schottky characteristics in almost all cases. It was observed that there was not a universal combination of Mo:Al that yielded the best ohmic performance irrespective of the wafer structure or source. However, an annealing temperature range of 525°C–575°C and a Mo:Al ratio in the range 1:3–1:4 were observed to yield excellent ohmic contacts with contact resistances down to ~0.2±0.05 Ω-mm and specific contact-resistivities down to ~1.0×10⁻⁶ Ω-cm². We will present comprehensive electrical results on contact resistance as a function of annealing temperature and annealing time for different Mo:Al ratios. Results on surface roughness, thermal stability, Auger electron spectroscopy, x-ray diffraction and XTEM studies will also be presented and discussed.

11:00 AM

N8, AlGaIn/GaN FETs with Un-Optimized Source/Drain Contacts for Rapid Extraction of Channel Mobility and Charge Concentration: *Michael Awaah*¹; O. N. Akpa¹; J. James¹; A. N. Guha¹; K. Das¹; ¹Tuskegee University

A two-mask process has been utilized for the fabrication of relatively long-channel Al_{0.2}Ga_{0.8}N/GaN FETs for rapid extraction of channel mobility and to assess the device worthiness of the material system. Circular geometry of the devices with wrap-around gate contacts provided device isolation. A 100 μm diameter dot formed the drain contact. The drain contact was surrounded by a ring-shaped gate that in-turn was surrounded by the source contact. Both the source-gate and drain-gate separation was 10 μm. Three different gate lengths 5, 7.5 and 10 μm were employed. In addition to FETs, the mask-set test included Ni/AlGaIn/GaN rectifying diodes, representative of the FET gate element and a set of TLM pads for the evaluation of the source/drain contact resistivity. A heteroepitaxial film of Al_{0.2}Ga_{0.8}N/GaN on a sapphire substrate was used in this study. The unintentionally doped Al_{0.2}Ga_{0.8}N, 20 nm in thickness was deposited on a 1 μm thick unintentionally doped GaN film, with donor concentration of ≈ 1×10¹⁵ cm⁻³. Sputter-deposited Ti/Au (20/150 nm) source/drain contacts were defined by photoresist lift-off and annealed at 800°C. A 75 nm thick Ni film was used as the gate contact. Surface passivation for these devices was obtained using a film of spin-on

SiO₂ deposited prior to source/drain metallization. Electrical measurements on these test structures yielded a contact resistivity of $2.0 \times 10^{-3} \Omega \cdot \text{cm}^2$. The rectifying diodes, representative of the FET gate contacts, yielded a barrier height of ≈ 1.1 eV. A sheet charge density of $\approx 1.1 \times 10^{13} \text{ cm}^{-2}$ at the Al_{0.2}Ga_{0.8}N/GaN interface, an apparent carrier concentration of $\approx 8.4 \times 10^{18} \text{ cm}^{-3}$ and a conduction band offset of 0.27 eV were also obtained from measurements on the rectifying diodes. The gate-to-drain voltage of up to 50 V was applied prior to the onset of s/d breakdown, and a drain current of ≈ 110 mA/mm were obtained for the 5, 7.5 and 10 μm gate-length devices. An FET channel mobility of $\approx 511 \text{ cm}^2/\text{V}\cdot\text{s}$ was extracted from the device transconductance of ≈ 20 mS/mm. In comparison, a Hall mobility of $900 \text{ cm}^2/\text{V}\cdot\text{s}$ was obtained from the material in the as-grown state. It is believed that the device processing in particular the anneal treatment that was employed to form the ohmic contacts had degraded the carrier mobility in the quantum well at the AlGaIn/GaN interface that forms the FET channel. In a subsequent design both circular and rectangular geometry device with gate lengths of 5, 10, 15, 25, 50, 75, 100 μm have been employed, as very long gate devices (fatFET structures) are better suited for the extraction of low-field channel mobility.

11:20 AM Student

N9, Electrical Contacts to Undoped and Sulfur-Doped Nanocrystalline Diamond Films: *Pranita Kulkarni*¹; Yingjie Tang²; Franz Koeck²; Robert Nemanich²; Lisa Porter¹; ¹Carnegie Mellon University; ²North Carolina State University

Nanocrystalline diamond (NCD) films are being intensively researched for a variety of potential applications, such as optical windows, electrochemical electrodes, and field emission displays. In this study Zr, Ti, Cu and Pt on intrinsic and lightly sulfur-doped (n-type) NCD films were characterized electrically and photoelectrically. Intrinsic and sulfur-doped nanocrystalline diamond films were synthesized on 1 in. diameter quartz substrates by microwave plasma assisted chemical vapor deposition. The films were grown at $\sim 800^\circ\text{C}$ and 20 torr chamber pressure with hydrogen as carrier gas and methane as carbon source. Sulfur incorporation was achieved by introducing a 50 ppm hydrogen sulfide in hydrogen mixture during growth. For electrical measurements the metals were deposited using electron-beam evaporation and were patterned in a circular TLM geometry using conventional photolithography. All metals showed linear (ohmic) current-voltage characteristics in the as-deposited state. The Schottky barrier heights (SBHs) at the metal-film interface were investigated using x-ray and ultra-violet photoelectron spectroscopy. The undoped NCD films exhibited a negative electron affinity and a band gap of 3.7 eV. The SBHs were calculated based on this band gap measurement and the consistent indication from Hall measurements that the films are n-type. The SBHs were calculated from shifts in the core level (C1s) peaks obtained immediately before and after in-situ, successive metal depositions. The SBHs for Zr, Ti and Pt on undoped films were calculated to be 2.8, 2.5 and 3.2 eV, respectively, which gives a slope parameter of 0.38. The S-doped films also showed increasing SBHs with metal work function: 1.8, 1.9 and 2.3 eV for Zr, Ti and Pt, respectively, with a slope of 0.35. These results appear to agree with the previous results on similar films that indicate upward band bending at the surface.^{1,2} In general accordance with the barrier height trends, the specific contact resistivity (ρ_c) values increased with the metal work functions for both undoped and S-doped films. For the undoped films ρ_c increased from $3 \times 10^{-5} \Omega \cdot \text{cm}^2$ for Zr to $6.4 \times 10^{-3} \Omega \cdot \text{cm}^2$ for Pt. The ρ_c values for the S-doped films were approximately two orders of magnitude lower than those for the undoped films: $3.5 \times 10^{-7} \Omega \cdot \text{cm}^2$ - $4.5 \times 10^{-5} \Omega \cdot \text{cm}^2$ for Zr and Pt, respectively. The Hall-effect measurements indicated that the average sheet resistivity and carrier concentration values were $0.16 \Omega \cdot \text{cm}$ and $3.5 \times 10^{18} \text{ cm}^{-3}$ for undoped films and $0.15 \Omega \cdot \text{cm}$ and $4.9 \times 10^{19} \text{ cm}^{-3}$ for S-doped films. ¹Koeck, F.A.M.; Garguilo, J.M.; Nemanich, R.J.; Gupta, S.; Weiner, B.R.; Morell, G., *Diamond and Related Materials*, 12, 2003 p 474 - 480. ²Koeck, F.A.M.; Nemanich, R.J., *Diamond and Related Materials*, 14, 2005 p 2051 - 2054.

11:40 AM Student

N10, Investigations of UV-Transparent Nanocrystalline Diamond Films as a Type-II Heterojunction to 4H-SiC: *Marko Tadjer*¹; Karl Hobart²; Joshua Caldwell²; Tatyana Feygelson³; James Butler²; Kendrick Liu²; Mario Ancona²; Fritz Kub²; ¹University of Maryland; ²Naval Research Laboratory; ³SAIC

Nanocrystalline diamond (NCD) thin films are of interest due to their large bandgap and excellent thermal properties, which make them attractive for power device applications.¹⁻³ While the UV transparency of NCD films has been previously reported on other substrates,⁴ here we show that both doped and undoped NCD films can be used as a contact for both optical and electrical measurements on both n- and p-type 4H-SiC. In this study, NCD films on both n- and p-type SiC were investigated for use as a transparent Schottky contact to allow the simultaneous electrical and optical characterization of defects within SiC epitaxial layers. Three sample structures were used, with the NCD grown by microwave plasma-enhanced chemical vapor deposition: (1) 0.5 μm thick B-doped p+ NCD on an n- 4H-SiC epitaxial layer, (2) same NCD film on a p- 4H-SiC epitaxial layer, and (3) an unintentionally-doped NCD film on an n- 4H-SiC epilayer. All 4H-SiC epilayers were grown on 8° off-axis n+ 4H-SiC substrates. The n- and p-type SiC epilayers had thicknesses of 5 μm , 10 μm , and 10 μm , respectively, and carrier concentrations were approximately $1 \times 10^{16} \text{ cm}^{-3}$. Circular Al contacts were deposited onto the samples for I-V and C-V measurements and gridded patterns in the Al film were used for optical transparency. In addition, transfer length method (TLM) and circular TLM contacts were formed in order to measure film properties. No post-evaporation annealing was performed. I-V measurements indicated an extremely high degree of Schottky-like rectification, which suggested a metallic nature for the p+ NCD film. The data analysis found activation energies of 0.85 eV and 0.74 eV for the p+ NCD on n-type and p-type SiC, respectively. The measured activation energy for the undoped NCD sample was 0.48 eV. Silvaco-simulated energy-band diagrams of the B-doped NCD heterojunctions indicated Type-II behavior. One possible conduction path is from the conduction band of the SiC into the B-impurity band of the NCD, which would explain the low turn-on voltage that was observed in the I-V measurements. Optical beam induced current (OBIC) and photoluminescence imaging revealed a high degree of UV transparency, thereby allowing high resolution imaging of defects within the underlying semiconductor epilayer. Therefore, NCD films are ideal as a high-temperature surface-passivating contact for optical characterization of defects in SiC. ¹J. Phillip, P. Hess, T. Feygelson, J.E. Butler, S. Chattopadhyay, K.H. Chen, and L.C. Chen, *J. Appl. Phys.* 93, 2164 (2003). ²M. Nesladek, D. Tromson, C. Mer, P. Bergonzo, P. Hubik, and J. Mares, *Appl. Phys. Lett.* 88, 232111 (2006). ³Y. Itoh, Y. Simikawa, H. Umezawa, and H. Kawarada, *Appl. Phys. Lett.* 89, 203503 (2006). ⁴Z. Remes, A. Choukurov, J. Stuchlik, J. Potmesil, M. Vanecek, *Diamond & Related Materials* 15 (2006).

Session O: Nanostructure Physics and Characterization

Thursday AM
June 21, 2007

Room: 155
Location: DeBartolo Hall

Session Chairs: James Merz, University of Notre Dame; Edward Yu, University of California, San Diego

8:20 AM

O1, Radiative Recombination of Charged Excitons and Multi Excitons in CdSe Quantum Dots: *Alberto Franceschetti*¹; M. Claudia Troparevsky¹; ¹National Renewable Energy Laboratory

The primary decay channel for charged excitons and multi excitons in colloidal quantum dots consists of non-radiative, Auger electron-hole recombination. Recently, optical emission from short-lived, multi-particle excited states has been observed in CdSe colloidal quantum dots, using either time-resolved, femtosecond photoluminescence spectroscopy, or quasi-continuous-wave optical pumping. In those experiments, the appearance of additional emission peaks - both to the red and to the blue of the single-exciton emission peak - at high excitation intensity was attributed to the

radiative recombination of charged excitons and multi excitons. However, the origin of the observed emission lines is still highly controversial. In particular, a well resolved, high-energy emission band - about 100-250 meV to the blue of the single-exciton main emission peak - was attributed to the radiative recombination of a p-like electron with a p-like hole in a tri-exciton complex (three holes and three electrons). This interpretation, however, is problematic, because in CdSe quantum dots up to several nanometers in diameter the two spin-degenerate energy levels at the top of the valence band are both s-like, and can accommodate up to four holes. As a result, one expects that in the tri-exciton ground state the p-like valence-band states are not occupied by holes, thus making p-p radiative recombination impossible. Using atomistic pseudopotential calculations, we have calculated the optical emission spectra of excitons, multi-excitons and charged excitons of CdSe quantum dots ranging in size from 3 to 6 nm. We find that (i) the main emission peak of charged multiexcitons, which originates from the recombination of an s-like electron with an s-like hole, is significantly blue shifted with respect to the neutral monoexciton emission peak. (ii) The p-like hole states are populated in the tri-exciton ground state of CdSe quantum dots, because of the relatively small Coulomb repulsion between s-like and p-like hole states, which leads to a non-aufbau occupation sequence of the hole levels. The occupation of p-like hole states in the tri-exciton ground state explains the observed high-energy peak in the tri-exciton emission spectrum. (iii) The observed temperature dependence of the tri-exciton p-to-p emission peak originates from the dark-bright splitting of the tri-exciton ground state. Our results provide a consistent explanation of the physical origin of charged-exciton and multi-exciton emission lines in CdSe quantum dots.

8:40 AM

O2, Conduction Band and Electronic Properties of AIP-GaP Superlattices: M. P. Semtsiv¹; O. Bierwagen¹; S. Dressler¹; W. Masselink¹; V.V. Rylkov²; J. Galibert²; M. Goiran²; J. Leotin²; ¹Humboldt University Berlin; ²Laboratoire National des Champs Magnétiques Pulsés

Both AIP and GaP are indirect-band-gap semiconductors with their conduction band minima at X. Together, they form a type-II heterojunction system, with the X-valleys of the AIP lower in energy than those of GaP, but with the lowest-lying states for holes in the GaP. The system has attracted attention for two potential applications: 1) Green-to-yellow light emission with relatively high intensity due to the folding of the Brillouin zone;¹ 2) intersubband transitions in the THz frequency range including a range of 30–40 μm that is difficult in GaAs-based systems due to optical phonons.^{2,3} We have investigated the electronic properties of a series of AIP-GaP superlattices with varying AIP thickness. These structures were grown using gas-source MBE on GaP(001) substrates. Cyclotron resonance, quantum Hall effect, and Shubnikov-de Haas oscillations were measured for modulation-doped structures (the GaP layers Si-doped) at magnetic fields up to 50T. Intersubband optical absorption measurements were also carried out for other AIP-GaP superlattices with doped AIP wells. The results taken together allow an accurate determination of the effective mass tensor for the conduction band minimum of AIP, its symmetry and location in momentum space, the donor doping efficiency for AIP, and the deformation potential for the strained AIP X-valleys. The AIP-GaP superlattices can be separated into two classes based on AIP well width with fundamentally different properties. Both the strain due to 0.3% lattice mismatch between the AIP and GaP and the asymmetric effective mass lead to a splitting of the X valleys. The deformation potential pushes the longitudinal valley higher while the increased energy due to the quantum size effect is more pronounced for the transverse valleys. Thus the electrons should reside in the transverse valleys of wider AIP wells but in the longitudinal valleys of narrower wells. The quantum Hall together with Shubnikov-de Haas measurements are consistent with this expectation and further show that the X valleys are located at the Brillouin zone edge and not as Camels-back as in GaP. Further, the cyclotron resonance data indicate that $m_x = 0.28m_0$ and $m_y = 1.0m_0$. Comparing superlattices with varying AIP well thickness, the cross-over from narrow to wide is determined to lie between 4.5 and 6.5 nm, most probably at about 4.9 nm, allowing a determination of the X-valley deformation potential for AIP. ¹F. Issiki, S. Fukatsu, and Y. Shiraki, Appl. Phys. Lett. 67, 1048 (1995). ²M. P. Semtsiv, U. Müller, W. T. Masselink, N. Georgiev, T. Dekorsy, and M. Helm, Appl. Phys. Lett. 89, 184102 (2006). ³M. P. Semtsiv, S. Dressler, W. T. Masselink, V.V. Rylkov, J. Galibert, M. Goiran, J. Leotin, Phys. Rev. B 74, 041303 (2006).

9:00 AM

O3, Anisotropic Tunneling-Mediated Transport in Two-Dimensional Arrays of InAs Nanostructures: Oliver Bierwagen¹; W. Masselink¹; ¹Humboldt University Berlin

We have investigated the anisotropic electronic transport in planar arrays of coupled quantum wires and quantum dots. Our data show that the transport anisotropy arises not only from the structural anisotropy of the nanostructures, but primarily from directional-dependent coupling between the structures. Thus, even in arrays of quantum dots that are isotropic in shape, the electronic transport can be anisotropic. Finally, a switching device based on transport anisotropy is described and characterized. Using gas-source MBE we prepare InAs quantum dots, quantum dashes, and quantum wires on InP substrates. The shape of the self-organized nanostructure is controlled by substrate orientation and growth conditions.¹ Generally, quantum wires can be formed along the [-110] direction of the InP (001) substrate. When wire formation is inhibited, an unordered array of quantum dots forms. We have prepared a variety of such modulation-doped InAs nanostructures and investigated the direction-dependent transport. Transport anisotropies as high as 30 for electrons and 100 in the case of p-type modulation-doped structures are measured. Surprisingly, the transport in arrays of quantum dots without an obvious structural anisotropy is clearly anisotropic, with the electron mobility in the [-110] direction 10 times as high as in the [110] direction. The results can be explained, however, through small differences in the tunneling-mediated coupling in the two directions. Based on the temperature-dependent transport data and a model based on direction-dependent coupling between adjacent nanostructures, we conclude that the transport anisotropy is primarily due to the difference in tunneling in the two directions. For both electrons and holes, the anisotropic transport is described in terms of coupling and mean free path within the nanostructure. In the case of p-type nanostructures, the transport in the low-mobility direction is through hopping. By applying a gate electrode to the top of the nanostructures, we are able to control the transport anisotropy through control of the coupling. The largest degree of anisotropy control demonstrated is a factor of 2. Based on this demonstrated gate-controlled transport anisotropy, a 5-terminal switching device is described and characterized. ¹O. Bierwagen and W. T. Masselink, Appl. Phys. Lett. 86, 113110 (2005).

9:20 AM Student

O4, Infrared Reflectivity Spectroscopy of Optical Phonons in Short-Period AlGaN Superlattices: Joseph Herzog¹; Alexander Mintairov¹; Kai Sun¹; Yu Cao¹; Debdeep Jena¹; James Merz¹; ¹University of Notre Dame

GaN and AlN compounds have been proven useful in wide bandgap microelectronics and optoelectronics. Properties of bulk GaN and AlN have been studied extensively; however, many characteristics of AlGaN superlattices are not well known. In particular, the properties of phonons, which greatly decrease electron mobility due to scattering, have not been determined. Note that effects of phonons are not always negative; for example, phonons can be useful for heat dissipation. In order to determine phonon properties, infra-red reflectivity spectra were measured on bulk semiconductors and on short period superlattices (SPS) which have been grown by high quality molecular beam epitaxy (MBE). The superlattices were grown on a thin (30-70nm) GaN buffer layer which was deposited on a sapphire substrate. Each superlattice consisted of 300 periods of alternating layers of GaN and AlGaN, each containing between 1 and 8 monolayers. The structure of each was measured by X-ray diffraction. Next, each sample's reflectivity was measured at a 15° incidence angle using a Bruker IFS-66V spectrometer in the range 400-2000 cm⁻¹. From these experimental spectra the dielectric function, and hence the optical phonon properties (namely phonon frequency and phonon damping) can be determined. Mapping the experimental spectra with theoretical calculations determined the longitudinal and transverse optical phonon energies and damping that were present in the AlGaN superlattices. Different AlGaN superlattice combinations were studied and plots of phonon energies versus material composition were obtained. These results prove useful in engineering phonons at specific frequencies. Furthermore, new phonons were discovered that were not present in bulk AlN and GaN. The theory of "confined phonon modes" proved useful to predict some of these new phonon modes. Finally, phonon characteristics were measured as a function of temperature, confirming that phonon energies decrease with increasing temperature, as expected.

THURSDAY AM

9:40 AM Student

O5, Transport Properties and Applications of Quantum-Wire Solids: *Amol Singh¹; Masaru Kuno¹; Huili Xing¹; Debdeep Jena¹; ¹University of Notre Dame*

Semiconducting nanowires (NWs) are synthetic materials which have tunable optical and electrical properties favorable for applications in wearable displays, bio-sensors, photodetectors etc. When assembled into dense connected networks on insulating surfaces, they form semiconducting films that can be called quantum-wire solids, analogous to the widely studied quantum-dot solids formed from semiconducting nanocrystals (NCs). Due to the quantum confinement of carrier wave functions, transport in quantum-dot solids occurs by hopping and by charging/discharging of the NCs, reducing both the conductivity and the speed of devices using them as the active layers. On the other hand, in quantum-wire solids, we can take advantage of delocalized carrier wavefunctions along the nanowire axes, resulting in superior transport properties, while retaining most advantages of size-confinement and offering new capabilities such as polarization sensitivity. In this work, we present our studies of the transport properties of quantum-wire solids made of ultrathin semiconductor NWs covering a range of bandgaps from the visible to the IR, and demonstrate polarization-sensitive quantum-wire solid photodetectors. A high yield and low cost solution-based growth technique called solution liquid solid (SLS) was employed to grow NWs of CdSe (bulk gap ~1.74 eV), CdTe (~1.5 eV), PbS (~0.34 eV) and PbSe (~0.27 eV). The wires were 10-20 nm in diameter and 1-10 microns long. Dense, connected quantum-wire solids were made by drop casting NWs on glass and subsequent metal evaporation and annealing. The dark conductivities of CdSe, and CdTe quantum-wire solids were found to vary as $\exp(-E_a/2kT)$ at high temperatures (360K–470K), where E_a is close to the respective bulk bandgaps. At lower temperatures, the conductivity saturates, indicating the presence of a very low concentration of residual dopant impurities. The residual conductivity allowed us to extract a residual impurity doping $\sim 10^2$ cm⁻³, indicating a very high level of purity of the wires. The low residual impurity densities also confirm the fact that the growth kinetics in the solution-synthesis of NWs and NCs makes them difficult to dope. At higher temperature thermally generated charges determine the transport and dark current increases by 5 orders of magnitude in temperature range 360K–470K. Under optical illumination, the photocurrent is > 3 orders of magnitudes larger than the dark current and above a critical temperature, thermally generated carriers exceed optically generated one and the photocurrent and dark current become essentially the same. Photocurrent spectroscopy was performed on the quantum-wire solids, and band-edge photocurrent onset was observed, confirming the measured bandgap from absorption and emission measurements. Polarization-sensitive photodetectors were demonstrated with the CdSe quantum-wire solids. The responsivity of the photodetectors was in ~ 0.1 A/W range.

10:00 AM Break

10:20 AM Student

O6, Nanometer-Scale Measurements of Confined States in and between InAs/GaAs Quantum Dots: *Vaishno Dasika¹; Jin Dong Song²; Rachel Goldman¹; ¹University of Michigan; ²Korea Institute of Science and Technology*

In the past decade, strain-induced self-assembled quantum dots (QDs) have enabled enormous advances in optoelectronics, including high performance infrared light-emitters and detectors. Further advances in light-emitters will require a narrowing of the density of states, which may be achieved through an improved understanding and control of the electronic effects of QD composition, size, and shape. We have explored the effects of composition gradients on the confined states in and between QDs. These QDs were grown with thick (~50 nm) GaAs spacers between QD layers to ensure that coupling would not take place between QDs from different layers. Cross-sectional scanning tunneling microscopy (XSTM) images reveal QDs with diameters typically between 14 nm and 40 nm and heights typically between 4 nm and 14 nm. Scanning tunneling spectroscopy (STS) spectra were acquired from different locations within the QDs, in comparison with regions of clean GaAs from the spacer layers. The room temperature STS spectra revealed a gradient in effective band gap across the length of individual QDs, with the smallest effective gap near the QD centers. This has been attributed to

the increased concentration of indium toward the center of the InAs QD. In addition, this gradient in effective band gap across the QD was mostly accommodated in the conduction band of the QD. Both of these effects were observed in QDs of different sizes. For the wetting layers (WL) between the QDs, we used STS to measure the effective bandgap in various regions of the WL. Regions of the WL with a higher concentration of In displayed a smaller bandgap than regions of the WL with a lower concentration of In. Thus, we have confirmed that the WL surrounding QDs is not homogeneous. To explore the STS energy resolution, low temperature measurements of both the QDs and WLs will also be discussed.

10:40 AM Student

O7, Composition Analysis of Silicon and Germanium Nanowires Using Pulsed-Laser Atom Probe Tomography: *Daniel Perea¹; Eric Hemesath¹; Jessica Lensch Falk¹; Lincoln Lauhon¹; ¹Northwestern University*

Semiconductor nanowires of controlled composition and doping are useful building blocks for nanoelectronic and nanophotonic devices. Metrological techniques capable of exploring spatial variations in nanowire composition are needed to correlate electronic and optical properties with the dopant concentration and composition. Of particular interest in nanowires grown by the vapor-liquid-solid (VLS) method is whether or not atoms from the catalyst seed particle become incorporated into the nanowire during growth, a topic of frequent speculation. Pulsed-laser local electrode atom probe tomography (PL-LEAP) is capable of analyzing the composition of semiconductors with sub-nanometer spatial resolution and ppm sensitivity, and was recently shown to be well-suited for the analysis of individual semiconductor nanowires.¹ We used PL-LEAP to analyze the composition of individual Si and Ge nanowires grown by the VLS mechanism with Au catalysts and silane and germane as the source gas, respectively. Uniform Si and Ge nanowires and nanowire heterostructures were grown epitaxially on Si(111) and analyzed at temperatures of 50-100K and pulse energies of 0.02-0.5 nJ. Runs of up to 8 million atoms were collected for silicon nanowires, with typical analysis volumes 20 nm in diameter and hundreds of nanometers in length. By analyzing several nanowires grown under identical conditions, it was determined that the concentration of Au in silicon nanowires is less than $\sim 10^{17}$ atoms-cm⁻³. In ideal runs, there are zero background counts in the mass-to-charge ratio windows associated with Au species, indicating that this concentration is an upper bound limited by counting statistics. As with Si, Au atoms were not detected in Ge nanowires, enabling an upper bound of 7×10^{16} atoms-cm⁻³ to be established. While Au at these concentrations would still have a significant effect on the lifetime of minority carriers in bulk silicon, our recent studies of minority carrier diffusion, to be reported in another session, indicate that surface recombination dominates minority carrier lifetime in these nanowires. PL-LEAP measurements have been extended to boron-doped silicon nanowires grown in the presence of diborane, and to Si-Ge core-shell and axial heterostructures. B atoms are detected at concentrations well below the gas phase concentration ratios, indicating an incorporation efficiency less than unity. Ge shells were used as radial markers to quantitatively determine the radial distribution of dopant atoms within the nanowire, and isolate surface doping from dopants incorporated through the catalyst. ¹D. E. Perea, J. L. Lensch, S. J. May, B. W. Wessels, and L. J. Lauhon, Applied Physics A-Materials Science & Processing 85, 271-275 (2006).

11:00 AM

O8, Nanoscale Strain and Composition Mapping in Quantum Dots Using Kelvin Probe Force Microscopy: *Yossi Rosenwaks¹; S. Shusterman²; A. Schwarzman¹; A. Raizman²; A. Sher²; Y. Paltiel²; ¹Tel-Aviv University; ²Soreq Nuclear Research Center*

One of the key factors in improving quantum dots (QDs) electrical properties and QDs based devices is the ability to control the crucial parameters of composition, doping, size, and strain distribution within the QDs, as well as the crystalline structure at the QDs substrate interface and surfactant layers. Any attempt to improve growth conditions and performances would largely benefit from strain distribution and composition variations measurement within and around the dots. We present ultra-high vacuum Kelvin probe force microscopy (KPFM) measurements of InSb quantum dots that enabled us to map the strain fields and composition variations within individual QDs. The QDs were grown on highly Te-doped GaAs, InSb, and GaSb (100

oriented substrates by the droplet heteroepitaxy (DHE) method. The KPFM measurements were based on a modified UHV AFM (VT AFM, Omicron Inc.) operated at pressure 10-10 mbar, where the topography is measured in the non-contact frequency modulation mode at the first cantilever resonance, while the AC voltage applied to the tip for the KPFM measurements is tuned to the second resonance frequency. The KPFM measurements conducted on the InSb/GaAs dots showed a 'bagel-shaped' surface potential in the circumference of each dot. In general, the dots work function may be affected by their composition changes due to interdiffusion or dissolving of the substrate material by the liquid In droplets, by mismatch strain in both the substrate and the QDs, doping variation, strain dependent piezoelectric band shifts, surface states, quantum effects, and 2D electron gas formation. Considering all these factors, and measuring the strain using high resolution cross-sectional TEM, we show that the CPD fluctuations are mainly due to strain which changes the dots bandgap, and gradual internal composition changes from InAs to InSb. Fitting the measured surface potential profiles of several dots has allowed us to accurately extract the strain and composition within and around each dot.

11:20 AM

O9, Detection of Microwave Magnetic Fields on Yttrium Iron Garnet Materials Using Heterodyne Demodulation on a Loop Probe Cantilever:

Charles Paulson¹; Dan van der Weide¹; ¹University of Wisconsin

This presentation describes a magnetic force microscopy technique that can be used for detection of localized high frequency magnetic moments of materials. This technique uses an integrated electromagnet on cantilever design. Current is driven through the electromagnet, creating a high frequency magnetic moment on the cantilever. Frequency mixing with high frequency fields from a sample leads to a force between the sample and cantilever that drives the cantilever into vibration. Therefore this technique can measure high frequency magnetic signals (from 10 MHz to ~3 GHz) by demodulation into the ~1kHz mechanical bandwidth (BW) of the cantilever. We demonstrate this method by measurement of ferromagnetic resonance (FMR) of Yttrium Iron Garnet (YIG) samples (a magnetic oxide material) near 3 GHz. The spectra are compared with the microwave network analyzer measurements confirming that we are demodulating the FMR signal down to the lower frequency of the cantilever vibration signal. Our frequency tunable detection system can clearly delineate the magnetostatic modes in the magnetic oxide material. Interestingly, our frequency resolution is set by the mechanical bandwidth of the cantilever, which is quite narrow (~1kHz). The combination of broad bandwidth and high resolution in a localized magnetic field detector is uncommon. Since we have a small loop on the end of the cantilever (a magnetic dipole) we can also use this dipole as a pick-up for detection of localized fields. This pick-up measurement can have high spatial resolution, but it suffers from parasitic pick-up on the feedlines to the loop. In regards to the heterodyne force detection, the speed of the spectral acquisition can be comparably fast relative to a commercial spectrum analyzer that is measuring signals in a similarly narrow BW. We also present an analysis of the interaction between the cantilever and the sample. One of the interaction forces is described in terms of the magnetic moments and fields that exist on the sample and the cantilever. We also discuss and present data related to calorimetric (heating) forces that are acting on the cantilever. Calorimetric effects have been described previously in work from other researchers. We compare and contrast our results with other vibrating systems such as tuningforks, and hard magnet tipped cantilevers, that can be made used to detect high frequency magnetic fields. Finally, we will mention a portable antenna that we have built that contains a compact interferometer that is capable of measuring high frequency magnetic fields and we will describe its potential uses in the field of magnetometry.

11:40 AM

O10, Late News

Session P: Chemical and Biological Sensors II

Thursday AM
June 21, 2007

Room: 131
Location: DeBartolo Hall

Session Chairs: Alec Talin, Sandia National Laboratories; David Janes, Purdue University

8:20 AM Student

P1, Electrical Characterization of Molecular Interactions via GaAs Junction Field Effect Transistors: Kangho Lee¹; Heeyeon Park¹; Albena Ivanisevic¹; David Janes¹; ¹Purdue University

Recent advances in discovering biomarkers for specific diseases, particularly cancers, have necessitated development of ultra-sensitive biosensors for early diagnosis of critical diseases. To detect small amount of biomarkers, it is imperative to develop efficient transducers that can convert biological interactions into quantifiable signals. Various detection schemes have been demonstrated on the basis of different transduction mechanisms by incorporating a quartz crystal microbalance, quantum dots, nanowires, etc. Among these, electrical transduction with conventional semiconductor devices has been considered as a promising candidate due to ease of integration and possibility of label-free detection. Although a number of devices consisting of planar semiconductor layers or nanowires have reported responses to various biomolecules, to date the detailed mechanisms behind electrical detection of biological interactions have not been elucidated, in part due to the limited number of studies which have characterized the chemical properties of the surfaces along with the electrical responses. In this study, GaAs junction field-effect transistors (JFETs) were fabricated to investigate the effects of organic adsorbates on device electrical characteristics and transduction of a biological interaction between TAT peptide and TAR RNA. The JFETs have a layer structure that consists of a 100 nm heavily-doped n-GaAs layer for low contact resistance, a 100 nm Si-doped ($5 \times 10^{17} \text{ cm}^{-3}$) n-GaAs channel layer, a 300 nm Be-doped ($5 \times 10^{16} \text{ cm}^{-3}$) p-GaAs layer for gate modulation via pn-junction depletion width changes, and a 100 nm Be-doped p-GaAs low-resistance buffer layer, which are grown on a p++ GaAs substrate by molecular beam epitaxy (MBE). Device isolation was achieved by mesa formation, Au/Ge/Au/Ni/Au source/drain contacts were lithographically formed and a backside gate contact was formed by e-beam deposition of Pt/Ti. Si_3N_4 was deposited for device passivation by plasma-enhanced chemical vapor deposition (PECVD), and active device and contact regions were exposed by dry-etching the Si_3N_4 layer. Finally, recess etching was performed to adjust threshold voltage (V_{th}). Mixed monolayers of 1-octadecanethiol (ODT) and TAT peptide (TAT) were solution-deposited on the GaAs surface, with the TAT providing selective binding sites for a specific RNA and the ODT serving to passivate the surface. Prior to immobilization of ODT and TAT onto devices, modified GaAs surfaces were characterized by X-ray photoelectron spectroscopy (XPS). The XPS analysis revealed that GaAs modified with a mixed monolayer of sequentially deposited ODT and TAT did not show surface oxidation peaks with ~30% of TAT in an ODT host matrix. GaAs JFETs functionalized with the mixed monolayer exhibited a negative V_{th} shift of 0.5V with comparable subthreshold slope, which indicates existence of net positive charges on the surfaces. Investigations of the reactivity of modified devices with TAR RNA and optimization of mixed monolayer formation are still in progress.

8:40 AM

P2, Resistivity Response of Hemin Functionalized InAs to Low ppm Levels of Nitric Oxide Gas: Michael Garcia¹; Scott Wolter¹; William Lampert²; Changhyun Yi¹; Maria Losurdo³; Giovanni Bruno³; April Brown¹; ¹Duke University; ²Army Research Office; ³IMIP-Consiglio Nazionale delle Ricerche

InAs structures are of interest for sensors and other devices due to the existence of an electron surface accumulation layer resulting from Fermi level pinning in the conduction band. The modification of the surface charges changes the concentration of this surface layer leading to the efficient

modulation of the sample conductivity. In this work, we explore InAs on InP substrates as a sensor platform for radical gases (such as NO and NO₂). NO's diverse roles in defense, biological, and environmental fields create interest in the development of selective and sensitive solid state sensors. In a controlled gaseous environment, InAs samples were probed for changes in resistivity while exposed to varying concentrations of NO and other analytes. Initial results show 1.4 ppm of NO inducing a +8% change in the sheet resistivity with trends that show increased response correlated with increased NO concentration. The increasing resistivity response indicates a depletion of the electron carriers in the surface accumulation layer, which causes upward band-bending. The NO₂ response was significantly greater than that of NO, which could be due to differences in electron affinities, ionized partial pressures, dipole moments, or catalytic activity of the surface. Additionally, the functionalization of the InAs surfaces with hemin porphyrins was explored for enhancing selectivity and sensitivity to NO and NO₂. X-ray photoelectron spectroscopy data revealed changes in surface chemical composition and valence band maximum following functionalization chemistry. The N 1s and Fe 2p core levels of functionalized InAs (at ~ 398.5 eV and 711 eV, respectively) indicate the presence of the Fe porphyrins. Furthermore, the functionalization process has been extensively examined and corroborated with spectroscopic ellipsometry analysis. The analyte concentration, sample conductivity, and surface band energy relationships are modeled in an attempt to elucidate experimental sensor response for recommended materials optimization.

9:00 AM

P3, Photoelectric Junctions between GaAs and Photosynthetic Reaction Center Protein: *Yossi Rosenwaks*¹; L. Frolov¹; S. Richter¹; I. Carmeli¹; H. Carmeli¹; ¹Tel-Aviv University

The possible use of proteins in solid-state electronic devices is intriguing because of their versatile structure and function but requires activity under dry environment. We report on the use of a robust cyanobacterial membrane protein photosystem I (PS I) with its outstanding photoelectronic properties to fabricate an active electronic junction between the protein and GaAs. The photoactive reaction center PS I, a nano-sized protein-chlorophyll complex that harvests photons with a quantum efficiency of ~1 is functional in a dry environment. The stable functional junction was achieved by covalently binding genetically engineered cysteine mutants of PS I to a chemisorbed monolayer of small connecting molecules on the GaAs surface. Although the PS I monolayer is oriented in the same direction on the surface of the crystals, Kelvin probe force microscopy measurements showed an induced photovoltage of 0.3 V and -0.47 V in PS I-coated p- and n-type GaAs, respectively. The photovoltage resulted from an opposite direction of an electron and hole transfer between PS I and the semiconductors due to a difference of almost -0.8 eV in the Fermi level energy of the p- and n-GaAs, providing direct evidence of an electronically coupled junction. The electronic coupling between the protein and inorganic semiconductors described here could pave the way to the use of hybrid bio-solid state systems in various electrooptical devices such as phototransistors as highly sensitive photo sensors.

9:20 AM

P4, Characteristics of Carbon Nanotube Field-Effect Transistor Biosensor without Top-Gate Metal Electrode: *Masuhiko Abe*¹; Katsuyuki Murata¹; Tatsuaki Ataka¹; Kazuhiko Matsumoto²; ¹Olympus Corporation; ²Osaka University

For home medical care in distant places, it is very important to develop compact and simple biosensors that can perform real-time measurements. For practical use, such a biosensor should display high sensitivity. Because its electron capacitance is very small, the carbon nanotube field-effect transistor (CNT-FET) is expected to be able to detect living biological molecules with high sensitivity. We succeeded in detecting proteins by using a top-gate CNT-FET. The proteins (antigens) react with antibodies on the top gate of the CNT-FET biosensor and the biosensor detects the electron charges of the antigens on the top gate. Therefore, the structure of the top gate has a significant influence on the performance of the sensor. In this study, we prepared a CNT-FET biosensor without a metal top gate. The antibodies were fixed directly onto the insulator that was located above the CNT channel. We investigated the influence of the top gate on the performance of the

sensor. In the sample CNT-FET, a single-wall carbon nanotube and silicon nitride were used as a channel and insulator, respectively. We used PSA and a-PSA for the measurement, where PSA and a-PSA were an antibody and an antigen, respectively. The a-PSA was physically adsorbed onto the silicon nitride of CNT-FET which is referred to as the PSA sensor. A silicone rubber wall was placed on the PSA sensor, where a solution of Tris buffer (pH 8.0) containing PSA was poured. The dependence of the drain current on the PSA concentration was measured. Tris buffer without PSA was also poured onto the PSA sensor. The PSA sensor displayed an n-type property, since the drain current increased when the top-gate voltage was swept in the positive direction. When Tris buffer containing 7000 nmol/L PSA was poured onto the PSA sensor at $V_{TG} = +1$ V, the drain current decreased by 57 nA compared to the case when a 0 nmol/L PSA test solution was used. The developed CNT-FET biosensor was demonstrated to be capable of detecting the protein under investigation. Furthermore, the drain current dependence on the PSA concentration was investigated, and the performance of the developed biosensor was compared to that of a CNT-FET biosensor with a metal top gate.

9:40 AM Student

P5, Fabrication and Electrical Properties of Nanoplate Field Effect Devices for Chemical and Biological Molecule Sensing: *Oguz Elilbol*¹; Bobby Reddy¹; Rashid Bashir¹; ¹Purdue University

Semiconductor field effect sensors enable the possibility of realizing cost effective, highly dense label-free sensors for the detection of chemical and biological species. Such sensors can be readily integrated with existing platforms for micro total analysis systems, or lab-on-a chip systems. In addition, field-effect devices realized using nanowires, or other materials and structures have proven to provide detection sensitivity and selectivity far surpassing current clinical alternatives. In this work we present the development and characterization of a biological sensor using conventional microfabrication methodologies. The resulting structure has a single crystal silicon active area of 20 nm in thickness, 30 microns in length and 2 microns in width. Electrical characterization results highlight the importance of contacts and of control of surface properties from the stand point of optimizing device sensitivity. The ease of fabrication when combined with the end versatility of the finished product validate such devices as highly useful and practical chemical and biological sensors. Fabrication of the nanoplate devices starts with a 4 inch SIMOX-SOI wafer, with a top silicon layer of 50 nm, and a buried oxide layer of 160 nm, with p-type doping. The top layer of the silicon was thinned down to 20 nm via dry oxidation. The active area of the device was defined by conventional lithography and dry etching. Next, the source and drain regions were boron doped using an implant mask. Contacts to the active area were defined by lifting off an adhesion layer of 20 nm titanium and 180 nm platinum. PECVD oxide was deposited as a metal passivation layer in order to minimize the parasitic conductance through the fluid environment. The oxide directly over the pad areas near the edge of the wafer were etched, and layers of 200 nm titanium and 800 nm of gold for wire bonding were deposited and defined by liftoff. Via lithography, windows above the active areas of the devices were defined through a photoresist mask. Lastly, individual dies were etched using BOE to expose the active area of the devices. Electrical testing of devices was performed before contact anneal, after contact anneal and after oxide passivation layer deposition. The substrate was used as a back gate in order to extract gate dependent electrical characteristics. Devices were observed to be highly sensitive to the interface charge formed as a result of the PECVD deposition, which dramatically shifted device threshold voltages tens of volts. Dry state electrical results obtained confirm the sensitivity of the nanoplate devices to surface charge, which is extremely advantageous for usage as an ultra-sensitive field-effect chemical/biological sensor. However, this also requires careful control of surface properties in order to achieve the maximum sensitivity with the devices.

10:00 AM Break

10:20 AM Student

P6, Fabrication and Characterization of Novel Three Terminal Nanochannel Devices for the Detection of Short Biomolecules: *Murali Venkatesan*¹; Samir Iqbal¹; Rashid Bashir¹; Dimitrios Peroulis¹; ¹Purdue University

Solid state nanopores offer immense potential as tools to replicate and understand the biophysics of single molecule transport through ion channels. In addition, nanopores, synthesized either biologically or fabricated on solid-state membranes, could potentially lead to rapid and reliable genome sequencing, vital in vast applications in biology and medicine. Solid state nanopores exhibit increased chemical, thermal, and mechanical stability over biological pores and can be fabricated using conventional CMOS fabrication processes. Thus, solid state nanopores have the flexibility of operating at high pH and elevated temperatures whilst allowing for integration with electrical contacts and optical probes. The translocation of negatively charged DNA molecules through nanometer sized solid state pores is conventionally done using two terminal electrophoresis. Using such two terminal techniques, various phenomena have been investigated and reported in the literature such as counterion condensation on biomolecules, discrimination of DNA molecules based on length and nucleotide composition and the conformational changes of long DNA molecules during translocation through the nanopore. The observed phenomena however, are often difficult to reproduce due to variations in pore wetness, oxide charges, induced charges in the Silicon-On-Insulator (SOI) membrane and the degree of counterion condensation on biomolecules. These factors heavily influence the dynamics of molecular transport through the nanopore. The effects of surface charges on pore conductivity, as a function of buffer concentration have been reported. Extending this concept, we propose a three terminal device that can regulate surface charges through the internal SOI layer thereby controlling channel conductance and potentially the transport characteristics of biomolecules through the nanochannel. We have fabricated a novel three terminal nanochannel device consisting of two external electrophoresis electrodes, in conjunction with a third electrode (gate electrode) integrated onto the SOI layer. Grounding of the SOI through the third terminal can remove static stray charges induced in the SOI layer. The SOI membrane is heavily doped and annealed during the pore fabrication process to achieve high conductivity for both AC and DC applications. Subsequent etch, oxidation and TEM shrinking steps are used to form the nanopore followed by wire bonding of the gate electrode to the SOI surface after localized removal of oxide. The electrical isolation of the third electrode is done using a Polydimethylsiloxane (PDMS) protective layer. In addition, electrical characterization of the third electrode is carried out. It is expected that the channel conductance at low molarities (<0.1M) may potentially be controlled by adjusting the bias on the third terminal. We have carried out two terminal electrophoretic measurements using short molecules (molecule length≈nanochannel length). The applicability of this three terminal device to short molecule measurements and the theoretical and experimental implications of such a device with the third terminal will be presented.

10:40 AM Student

P7, Biochemical Functionalization of Semiconductor Devices: Cation Selectivity and Surface Charges: *Samir Iqbal*¹; Edward Judokusumo²; Bala Murali Venkatesan¹; Dimitrios Peroulis¹; Demir Akin³; Rashid Bashir⁴; ¹Purdue University, Birck Nanotechnology Center, School of Electrical and Computer Engineering; ²Purdue University, Birck Nanotechnology Center, Weldon School of Biomedical Engineering; ³Purdue University, Bindley Bioscience Center, Birck Nanotechnology Center, Weldon School of Biomedical Engineering; ⁴Purdue University, Bindley Bioscience Center, Birck Nanotechnology Center, School of Electrical and Computer Engineering, Weldon School of Biomedical Engineering

Solid state technology has matured over decades and is now identified as a key component for realizing novel nano-structures. There are unparalleled and unmatched advantages in terms of cost, control, efficiency, and packaging of novel devices. These qualities of the semiconductor processing can be leveraged to fulfill the persistence need of biotechnology and medical diagnostics in design and development of ultrahigh sensitivity bio-sensors. Detection of deoxyribonucleic acid (DNA) can be achieved using CCD and FET-type devices in labeled and label-free manner. The DNA is immobilized by physical or chemical adsorption, called the probe, and target DNA is

captured from solution phase. The most important factor, not optimally realized in microarray format, is the single base mismatch selectivity at single molecule level. It is important to differentiate between the perfect complementary and mismatched target molecules, where mismatch of as low as one nucleotide may be important. We biochemically functionalized oxidized silicon chips and incorporated mismatch selectivity in the design of target-probe DNA molecules. The biochemical modification of the SiO₂ surfaces were characterized throughout the functionalization process and the mismatch selectivity was verified on surface bound DNA molecules by fluorescence labeling. The attachment chemistries were analyzed, comparing and characterizing the most suitable scheme, in terms of surface coverage based on the fluorescence tags on the probe and target DNA molecules. A scheme utilizing homo-bifunctional linker molecule was then identified and used for the probe DNA attachment to nanopore channels. Solid state nanopore channels made in Si/SiO₂ membranes have emerged as progenitors of rapid and cheap next-generation DNA sequencing "machines". First, as for other chemical sensors, sensitive electronic circuitry and photonic sensing capabilities can be integrated directly into a pore-membrane system. Secondly, simultaneous and automated analysis of hundreds of arrays of different channels can potentially be achieved with such an integrated system. Next, they are more robust to withstand wide range of temperature, analyte solutions properties, environments and chemical treatments that might be required for the target detection and to eliminate interference. The adopted biochemical functionalization scheme showed consistent probe-target hybridization efficiency and better stability and reproducibility of the DNA layer. Our derivatization showed that the surface tethered charges increased the conductivity of the pores but the nanopore cation selectivity did not increase, as previously reported. We will present the CMOS-compatible fabrication process, the measurement setup and the results of our experiments. The motives of such CMOS compatible biochemical functionalization can be wide ranging from biosensors to integrated circuits; to detect chemical or biological species in bio-sensors, or the controlled assembly of nano-devices and structures in nano-electronics and biophysical studies.

11:00 AM Student

P8, Hydrogen Interaction with Liquid Ga Nanoparticles Monitored by the Plasmon Resonance: *Pae Wu*¹; Maria Losurdo²; Tong-Ho Kim¹; Giovanni Bruno²; Henry Everitt¹; April Brown¹; ¹Duke University; ²Institute of Inorganic Methodologies and of Plasmas-Consiglio Nazionale delle Ricerche, and INSTM

Hydrogen storage and recovery is of great import to energy-related research efforts. Alternative energy based on hydrogen and fuel cell technology may alter the current transportation and energy landscape and playing a key role for enabling hydrogen-based energy technology is the safe, stable storage and recovery of hydrogen in a portable fashion. To this end, two main issues must be addressed-1) the synthesis of new materials able to store hydrogen and 2) detailed understanding of the chemical and kinetic mechanisms responsible for hydrogen chemisorption and release. The use of nanostructures for hydrogen storage is attractive since hydrogen adsorption is driven by its interaction with surface sites. Metal nanoparticles and, specifically, liquid Ga nanoparticles are interesting for two reasons-1) they can form various hydrides upon reacting with hydrogen and 2) they exhibit a plasmon resonance, which can be tuned in the NIR-VIS-UV range depending on particle size. We have begun spectroscopic ellipsometry (SE) monitoring of the liquid Ga nanoparticle plasmon response to H₂ and atomic H (by a remote plasma source) and observed plasmon sensitivity to chemical modification of the Ga nanoparticles induced by interaction with hydrogen. The resonance plasmon peak responds to the Ga-hydrogen interaction mainly by damping the plasmon resonance, which is proportional to the hydrogen dose. The SE therefore provides a non-destructive optical tool to monitor, in real-time, the hydrogen chemisorption and release kinetics. The Ga nanoparticles were deposited at room temperature in UHV molecular beam epitaxy growth chamber (Veeco GENII) onto Al₂O₃ substrates. We previously demonstrated that the Ga nanoparticle plasmon resonance can be monitored by SE and the resonance energy correlates to the average nanoparticle size. Observation of the Ga-hydrogen interaction is monitored in real-time via the imaginary part of the pseudodielectric function, ϵ_2, and at the plasmon energy ϵ_p decreases monotonically during H₂ exposure, but stabilizes and remains constant once the flow is stopped. The time dependence, *i.e.* the

interaction rate, is proportional to the H_2 flux with no evidence of saturation within the measurement range. When atomic H is exposed to the Ga nanoparticles the interaction is a strong and abrupt decay-unlike the linear time dependence observed for the H_2 exposure-suggesting higher activity between the atomic H and the Ga nanoparticles compared to H_2 . Termination of atomic H flux increases $\langle \epsilon_r \rangle$, which follows a 1-exp function, indicating the Ga plasmon resonance to atomic hydrogen is reversible. For both atomic and molecular hydrogen, we also examine the interaction dependence on average Ga nanoparticle size as well as the temperature dependence. H_2 recovery is also studied. Real time kinetic SE data are corroborated by AFM, XPS and XRD measurements.

11:20 AM Student

P9, Nanoparticle Light-Emitting Sol-Gel-Based Waveguide Formation and Characterization: *Jinlong Zhang*¹; Thomas Kuech¹; ¹University of Wisconsin-Madison

Nanoparticles (NPs) incorporation into waveguide structures is attractive as a potential optical emitter, including lasers. In the present study, a method of incorporating NPs within a multilayer sol-gel waveguide was developed as a tunable light-emitting source. Zirconia-omosal (organic modified silane) sol-gel layer was used as host matrix for the NPs, because of its high refractive index and optical transparency over a broad wavelength including the near-UV wavelength range. The waveguide structure was fabricated through spin-coating on a silicon substrate to facilitate the integration with other semiconductor components. In order to prevent the light leakage or loss to the silicon substrate, a silica-omosal layer with lower refractive index was coated on silicon substrate first. A 3D Beam Propagation Method was employed to simulate the light propagation within the multilayer waveguide. The thicknesses of component layers were optimized to obtain the maximum light confinement factor in the zirconia-omosal layer of 98%. The relationships between film thickness and spin rate, spin time were obtained experimentally. The literature preparations of zirconia-omosal sol-gel films reported have employed acetic acid as chelating agent. However, colloidal NPs are not stable in a low pH environment. Two types of NPs were incorporated into the zirconia sol-gel films: CdS NPs and CdSe/ZnS core/shell NPs. Both of types of NPs no longer exhibited photoluminescence emission after mixing with acid-based zirconia sol. A non-acid based zirconia-omosal sol using acetylacetone as chelating agent was therefore used as the NPs host material. The amount of acetylacetone was adjusted to achieve a comparable chemical reactivity for both the zirconia and silica precursors so that the components of the waveguide formed at the similar rates. The FTIR spectra of zirconia-omosal sol indicate the formation of hetero-linkage (Zr-O-Si). However, the presence of Zr-O-Zr bond was detected in all of the zirconia sol, indicating the reaction between zirconia precursors was preferred. As the ratio of chelating agent increased from 1 to 2, the film surface roughness after spin-coating decreased. No measurable luminescence was obtained from the CdS NPs in the non-acid based Zr sol. The CdS NPs have a low solubility in polar solvents due to the hydrophobic ligands attached to the NPs and hence could have aggregated or otherwise precipitated from the solution. CdSe/ZnS NPs, surface functionalized with the MUA ligands, had comparable luminescence in both the zirconia film and the initial water solution. Photoluminescence of CdSe/ZnS NPs with emission wavelengths at 550nm and 580nm were measured. These results indicate that a NP high concentration can be achieved directly into an engineered waveguide structure without degradation provided attention is paid to the chemistry of ligand detachment.

11:40 AM Student

P10, In Vitro Microfabrication Assembly of Mitotic-Spindle-Like Structures: *Ying-Ming Huang*¹; Maruti Uppalapati¹; William Hancock¹; Thomas Jackson¹; ¹Pennsylvania State University

In eukaryotic cells, biological motors, such as kinesin, move along microtubules transporting intracellular cargo. These motor proteins are also involved in assembling complex structures of microtubules, such as the mitotic spindle (Sharp et al., 2000). Building an in vitro model of the bipolar mitotic spindle with the correct orientation of microtubules can provide a test bed for in-depth study of the role of motors in cell division and underlying forces without interference from other force generating mechanisms. We have developed a process to produce simple spindle-like structures using functional microtubule modification, biotin-neutravidin linking,

and dielectrophoresis. For this process we first deposit a blanket layer of Cr (1000Å) onto quartz substrate. Electrodes are then patterned in the Cr layer using photolithography and wet etching. Next, lyophilized neutravidin is resuspended in BRB80 buffer and absorbed onto the substrate with 1 mg/ml concentration. The sample is then dehydrated in acetone and dried. The neutravidin is then selectively patterned by deep UV exposure from back side of the sample in an UV-ozone tool. The electrode patterns serve as a mask during neutravidin patterning. After neutravidin patterning, a solution which contains microtubules with biotinylated segments at the minus-end (microtubules are structurally polar, with a minus and plus end) is placed on the surface and covered by a coverglass to prevent solution evaporation. Next, a 5MHz, 40V p-p, electric signal is applied to the Cr electrodes and microtubules collect by dielectrophoresis (DEP) at the tips of the electrodes. Although the collection does not depend on microtubule orientation, only the biotinylated segments of the microtubule link to the neutravidin and any microtubules with incorrect orientation can be easily flushed away by solution exchange. This process therefore produces spindle-like structures of oriented microtubules aligned to electrode structures. These structures can be used to test the roles of specific biological motors and provide essential building blocks for biomolecular motor based devices and applications. ¹Sharp, D.J., G.C. Rogers, and J.M. Scholey. "Microtubule motors in mitosis", Nature 407(6800):41-47, 2000.

Session Q:

Silicon Carbide: Defects and Growth

Thursday AM
June 21, 2007

Room: 138
Location: DeBartolo Hall

Session Chair: Laura Rea, U.S. Air Force Research Laboratory

8:20 AM

Q1, Recovery of Forward Voltage Drift in 4H-SiC PiN Diodes via Low Temperature Thermal Annealing: *Joshua Caldwell*¹; Karl Hobart¹; Robert Stahlbush¹; Orest Glembocski¹; Kendrick Liu¹; ¹Naval Research Laboratory

Shockley stacking faults are of interest due to the affect they have upon the electronic behavior of SiC-based devices, in particular those associated with bipolar devices. While these affects on bipolar devices, such as PiN diodes, are well known, the mechanism and driving force for SSF propagation and annealing along with the associated V_f drift are still in question. Recent reports have shown that SSF growth in 4H-SiC may be reversed via low temperature (210-700°C) annealing. However, it is unclear if the associated drift in the V_f is also reversed. Here, we present data showing that through the annealing of highly-stressed and faulted 4H-SiC PiN diodes, a complete and repeatable recovery of V_f will be observed. By looking at the time-dependent changes in the V_f during either constant-current or constant-voltage stressing in comparison to the those observed during the thermal annealing of a single diode, we can ascertain that the mechanisms for these two processes are distinctly different. Furthermore, through diode stressing studies performed at elevated temperatures (25°C–242°C), we have found that these two competing processes lead to a quick saturation of the V_f drift at relatively low values (an 11.5X decrease in the saturation V_f at 250°C from room temperature), as the temperature is increased for a given applied current. To clarify, independent of the basal plane dislocation (BPD) density, device operation at elevated temperatures leads to a lower density of SSFs at V_f saturation relative to the room temperature levels for that device. This effect introduces some intriguing prospects showing that BPD densities may not need to be reduced to values as low as originally anticipated. Furthermore, highly stressed devices, when operated later on at elevated temperatures, appear to self-heal back to the corresponding temperature-dependent saturation V_f value. These results further indicate that while SSFs may be the preferred electronic energy state for the 4H-SiC material when under high current-injection conditions, this is not the case when the material is left at thermal equilibrium (without current injection). This implies that under high injection conditions that the relative energy levels of the faulted and unfaulted states are adjusted in a manner favoring the formation of

SSFs, however, once this bias is removed, the energy levels revert back to their thermal equilibrium positions, which favors the creation of unfaulted material. The fact that the SSF are somewhat stable at room temperature in the absence of current injection is testament to the presumed large activation energy of the process. Samples were provided by Cree, Inc.; ONR contract N00014-02-C-0302, monitored by Dr. H. Dietrich.

8:40 AM

Q2, Spectral Characteristics of Individual Si- and C-core Partial Dislocations Obtained by Optical Emission Microscopy: *Kendrick Liu¹; Robert Stahlbush¹; Serguei Maximenko¹; Joshua Caldwell¹; ¹U.S. Naval Research Laboratory*

Degradation in V_f of SiC diodes is associated with the formation of Shockley stacking faults (SSFs) in the active region. These SSFs have been revealed by x-ray topography and transmission electron microscopy to be bounded by partial dislocations with a Burgers vector of the type $1/3\langle 1-100 \rangle$. The leading basal plane dislocation (BPD) have been identified as the Si-core, Si(g), while the stationary trailing BPDs have been identified as the C-core, C(g). The spectra of the Si(g) BPD have been reported to have bands that peak around 1.8 eV^{1,3} and 2.87 eV.³ To the best of our knowledge, the spectra of the C(g) BPD have not been experimentally reported. In this report, electroluminescence (EL) and photoluminescence (PL) optical emission microscopy (OEM) techniques were used to characterize a sample with a *p-i-n* structure. This sample consisted of 100 microns of a lightly doped n-type ($\sim 10^{14}$ cm⁻³) and two microns of a highly doped p-type ($\sim 10^{18}$ cm⁻³) layer epitaxially grown on a 4H-SiC n-type substrate ($\sim 10^{18}$ cm⁻³). The substrate was off-cut at an 8° from the (0001) plane toward the [11-20] direction. Aluminum (Al) films of 0.7- μ m thick were deposited on the front and back to form the contacts. Gridded cells of 1.7 × 1.7 mm² were patterned on the front side. The openings in the Al grid allowed for imaging of features in the active epilayer and for the case of PL-OEM, allowed for UV excitation of electron-hole pairs. The spectra for individual Si(g) and C(g) partial dislocations were extracted from images obtained using OEM at various emission bands. Both the EL and PL techniques revealed similar spectra. The Si(g) spectra were independent of the carrier-injection level and had a spectral peak at 700 nm, consistent with reported spectra from a small area containing many partial dislocations.^{1,3} On the other hand, the C(g) spectra were strong function of the injection level. At 0.1 A/cm² injection, there was a near-IR band from 850 nm to longer wavelengths, which saturated at 1.0 A/cm². Thence, another band at 700 nm dominated. This C(g) band at 700 nm was broader, and its peak was about 3 times less intense than the Si(g) peak. Our results correlated well with existing models of deep level bands resulting from dangling bonds on reconstructed dislocations.^{4,5} ¹A. O. Konstantinov et al., Appl. Phys. Lett., 71(25), 3700 (1997). ²A. Galeckas et al., Appl. Phys. Lett., 81(5), 883 (2002). ³A. Galeckas et al., Phys. Rev. Lett., 96(2), 025502-1 (2006). ⁴A. T. Blumenau et al., Phys. Rev. B, 68(17), 174108-1 (2003). ⁵G. Savini et al., Faraday Discussions, 134, 353 (2007).

9:00 AM Student

Q3, Influence of Threading Dislocations on the Recombination Enhanced Partial Dislocation Glide in 4H-Silicon Carbide Epitaxial Layers: *Yi Chen¹; Michael Dudley¹; Kendrick Liu²; Robert Stahlbush²; ¹Stony Brook University; ²Naval Research Laboratory*

Silicon carbide (SiC), a material with significant advantages over conventional semiconductor materials (e.g., silicon and gallium arsenide) under high power, high voltage and high temperature circumstances, has been facing failure issues related to various defects including micropipes (MPs), triangular defects, stacking faults (SFs) and low angle grain boundaries (LAGBs) during its application in devices. The forward voltage drop observed in SiC bipolar devices under forward biasing has been attributed to the expansion of silicon-core (Si-core) Shockley partial dislocations (PD) generated by dissociation of perfect basal plane dislocations (BPDs) driven by the electron-hole recombination enhanced dislocation glide (REDG) process occurring along the Peierls valley of the PD. The Si-core PD is found to be mobile while the carbon-core (C-core) PD is stationary. Various interactions can occur when the expanding SFs encounter the forest dislocations, e.g. threading edge dislocations (TEDs) and threading screw dislocations (TSDs). Further insight into the nature of the REDG process can be provided via understanding these interactions so as to shed light on strategies to mitigate

its negative effects. In our study, electron-hole recombination enhanced glide of Shockley partial dislocations bounding expanding stacking faults and their interactions with threading dislocations have been studied in 4H silicon carbide epitaxial layers. Threading edge dislocations can be cut through by the expanding stacking fault without leaving trailing dislocation segments. In contrast, when the REDG driven stacking fault interacts with threading screw dislocations, the stacking faults are split by the threading screw dislocations, lying on different basal planes, due to the helical shape of the lattice plane surrounding the screw dislocation core. Trailing 300 partial dislocation dipoles are initially deposited in their wake and they quickly and spontaneously snap into screw orientation whereupon they cross slip and annihilate leaving a prismatic stacking fault on the (2-1-10) plane with displacement vector $1/3[01-10]$. The mechanism is discussed and a “kink pushing” model is proposed to interpret migration of the partial dipole via zig-zag configuration.

9:20 AM

Q4, Ti-Related Photoluminescence in 4H-SiC: *Serguei Maximenko¹; Jaime Freitas, Jr.¹; Evan Glaser¹; ¹Naval Research Laboratory*

Silicon carbide (SiC) is currently under intensive investigation as a promising material for high-power, high-frequency, and radiation-hardened environments electronic applications. The suitability of SiC for these applications is due to its attractive physical properties such as high breakdown field, high-saturated drift velocity, good radiation resistance, and high thermal conductivity. However, at the present time, commercially available SiC wafers contain various crystallographic defects. In addition to high density of extended defects drastically influencing performance of devices, impurities and a variety of point defects are present in the material. They often introduce deep levels in the bandgap. These defects can act as recombination or carrier trap centers, effecting the lifetime of charge carriers. Therefore, it is very important to understand the properties of particular impurities and lattice defects giving rise to deep levels in the band gap. One of such defects is Ti, which acts as an isoelectronic substitutional impurity for Si in SiC crystals. This impurity was previously studied by photoluminescence (PL) technique in 6H-SiC polytype. In the present work we report the temperature dependence of Ti-related photoluminescence in 4H-SiC grown by High Temperature Chemical Vapor Deposition. To the best of our knowledge, temperature-dependent studies of the Ti spectrum in 4H-SiC have not been previously reported. Experiments were performed with light polarization perpendicular ($E^\wedge c$) and parallel ($E//c$) to the crystal uniaxial direction. In the $E^\wedge c$ configuration, two lines associated with the recombination process involving the annihilation of excitons bound to Ti impurities (located at the hexagonal and cubic lattice sites) were observed. These sharp and intense no-phonon assisted lines, indicated by A1 and B1, are observed at energies of 2.8480 eV (4351.97 Å) and 2.7887 eV (4444.67 Å), respectively. It was found that the PL spectra strongly depend on light polarization and sample temperature. Most notably, it was found that the B1 line is not observed with the $E//c$ configuration. In addition, new lines appear at the high energy side of the no-phonon lines with increasing sample temperature. These lines are related to thermal activation of higher energy states associated with the lower energy levels A and B. The thermal activation energies for the new levels A2, A3, A4 and B2 obtained by thermal ionization studies are in good agreement with the spectral energy line separations.

9:40 AM Student

Q5, Determination of Dislocation Sense of Micropipe via Grazing-Incidence X-Ray Topography in 4H Silicon Carbide: *Yi Chen¹; Michael Dudley¹; ¹Stony Brook University*

Micropipes (MPs) are device-killing defects, reducing the breakdown voltage of bipolar device made from 4H-silicon carbide (SiC) significantly. Various techniques have been used to record the micropipes present in SiC bulk crystals and epitaxial layers, e.g., molten potassium hydroxide (KOH) etching and X-ray topography. Synchrotron white beam X-ray topography (SWBXT) of various geometries has been successfully utilized to record the closed-core threading screw dislocations (TSDs) and MPs in bulk crystals and epilayers. They appear as white circles of various dimensions surrounded by narrow dark rings in back-reflection geometry and the images taken have been found to be consistent with the simulation by the ray-tracing method. However, the dislocation sense of the elementary TSDs and MPs

cannot be revealed by either molten potassium hydroxide etching, or directly from back-reflection SWBXT images. Revealing the dislocation sense of the elementary TSDs and MPs can provide further insight into their propagation during bulk and epitaxial growth and may shed light on strategies designed to mitigate their deleterious effects on growth. Although sectional X-ray topography and reticulography have been used to determine the MP senses, difficulty in locating the dislocation core or applying fine mesh makes the practical manipulation time-consuming. On the other hand, determining the MPs with relatively smaller Burgers vectors is restricted by the dimension limit of the grid element or the resolution of the X-ray film. Transmission cross-section X-ray topography is a destructive method to determine the MP sense, where cross-sectional samples are needed. A novel, non-destructive method by plan-view grazing-incidence X-ray topography using pyramidal plane reflection to determine the MP sense is introduced. Computer modeling using the ray-tracing method has been used to simulate the images of micropipes in grazing-incidence geometric X-ray topography of 4H silicon carbide using pyramidal (11-28) reflection. Simulation results indicate that the images of micropipes in 4H silicon carbide appear as slanted white ellipses with narrow arcs of dark contrast against the end of the long axes. The different orientations between the images of the left-handed and right-handed micropipes in grazing-incidence topographs using pyramidal plane reflection provide an effective way to discern their senses. Transmission cross-section SWBXT using basal plane reflection has been used to verify the sense determination mechanism by grazing-incidence SWBXT. Consistency between the dislocation sense deduced from plan-view grazing-incidence and transmission cross-section SWBXT images confirms the sense determination of micropipes by grazing-incidence X-ray topography using pyramidal plane reflection.

10:00 AM Break

10:20 AM Student

Q6, Step-Induced Stacking Faults in 3C-SiC Heterofilms: Further Motive for Reducing Screw Dislocation Density in 4H-SiC Substrates: Kevin Speer¹; Philip Neudeck²; David Spry³; Andrew Trunek³; Pirouz Pirouz¹; ¹Case Western Reserve University; ²NASA Glenn Research Center; ³Ohio Aerospace Institute, NASA Glenn Research Center

Encouraging electrical measurements and time-lapse electroluminescence (EL) images have been presented previously on the electrical and structural stability (i.e., absence of V_f drift) in bipolar pn diodes made from 3C-SiC grown atop 4H-SiC mesas. Two types of 3C devices were studied: those fabricated from *defect-free* 3C films grown on 4H mesas that were successfully rendered atomically flat using step-free surface heteroepitaxy; and those made from *defective* 3C films which were grown on 4H mesas with atomic-scale steps. The latter mesas could not be rendered atomically flat due to the presence of one or more threading screw dislocations, which are themselves perpetual step sources. In this work, a combination of site-specific cross-sectional TEM and defect-preferential etching (DPE) in molten potassium hydroxide (KOH) has been conducted on the 3C films. The results indicate that the luminescent bright-line defects in the 3C films are inclined {111} stacking faults penetrating the diode junction and intersecting the (111) diode surface. Additionally, very high densities of isolated etch pits (10^6 to 10^8 cm⁻²) are observed in the defective 3C films. This stands in contrast to 3C films nucleated on *step-free* 4H mesas, which have orders-of-magnitude fewer etch pits and stacking faults. With these observations in hand, we contend that the high density of isolated etch pits and stacking faults is a direct consequence of substrate steps on the 4H growth mesas at the onset of two-dimensional 3C nucleation—and fundamentally, due to the existence of threading screw dislocations. Our results imply that deposition-related stacking errors are not the primary defect formation mechanism. So in addition to the presentation of our XTEM and DPE results—and consistent with the observed data—a step-related formation mechanism will be discussed. This mechanism is based on deregistered Si-C bilayers at the coalescence of neighboring islands which were nucleated across “non-unit” (i.e., $\neq 1$ nm) steps.

10:40 AM Student

Q7, 3C-SiC Growth on Different Silicon Orientations: Christopher Frewin¹; Andrea Severino²; Ruggiero Anzalone²; Francesco La Via²; Stephen Saddow¹; ¹University of South Florida; ²IMM-CNR

3C-SiC growth has been carried out in a horizontal hot-wall CVD reactor in order to optimize the process using a low pressure (400 Torr) carbonization step followed by the growth of a thick 3C-SiC film at reduced pressure (100 Torr regime). Films grown under optimized conditions on (100) Si showed a low density of voids at the 3C-SiC/Si interface and a smooth surface indicating the absence of carbon particles and hillocks on the 3C-SiC surface. In order to understand the initial stage of formation of the thin 3C-SiC layer on a Si substrate with three different orientations (nominally (100) Si, (110) Si and (111) Si), each step of the growth process was monitored and studied. In particular attention was focused on (i) the initial thermal ramp from room temperature to the carbonization temperature of 1135°C, (ii) the effect of different carbonization step processing times, the thermal ramp from the carbonization step towards the growth temperature with (iii) and without (vi) the introduction of silane during this ramp and, finally, (v) on the growth step itself. For comparison, we repeated each process while performing the carbonization step at both 400 Torr and 760 Torr. Silicon carbide nucleates on the Si surface by first carbonizing the surface via the thermal cracking of a carbon-containing precursor (propane in our case). Once SiC nucleates there is a growth and coalescence of each nuclei to form a uniform and flat layer on the Si substrate. For long carbonization times in LPCVD carbon particles form on the top of the surface with hillocks and large voids underneath the interface. In the APCVD regime a rough interface was obtained leading to 3C-SiC films with defects and highly rough surfaces. The growth process gives different results based on the orientations of the substrate involved. While (100) Si and (111) Si show a similar behavior, under the same growth conditions 3C-SiC on (110) Si substrates resulted in a polycrystalline film. For such an orientation XPS analysis of the C 1S peak revealed an excess of carbon on the buffer layer, with a peak binding energy correlated to SiC. The role of the carbonization process is confirmed to be critical for the subsequent growth of less defective 3C-SiC resulting in high-quality material using an LPCVD reactor. The grown films have been characterized using optical microscopy, atomic force microscopy (AFM), x-ray photoelectron spectroscopy (XPS) and, on select samples, transmission electron microscopy (TEM). These measurements show that growth on the (100) Si surface is superior to growth on the (111) and (110) substrate orientations. However the process was optimized for this orientation and additional studies are being performed to optimize growth on the other orientations, which will be presented.

11:00 AM Student

Q8, Reduced Temperature 3C-SiC on Si Epitaxial Growth via HCl Additive: Meralys Reyes¹; Ian Haselbarth¹; Stephen Saddow¹; ¹University of South Florida-Tampa

A 3C-SiC growth process that yields deposition rates up to 2.5 $\mu\text{m}/\text{h}$ has been developed on silicon substrates oriented in the $\langle 100 \rangle$ direction at a temperature of 1250°C. A low-pressure horizontal hot-wall CVD reactor was used to carry out the deposition experiments. The standard $\text{SiH}_4/\text{C}_3\text{H}_8$ dual precursor chemistry with hydrogen (H_2) as the carrier gas was employed. In addition, hydrogen chloride was added to the gas mixture as a growth additive. The 3C-SiC growth was conducted in a two step process. First, the substrate was carbonized for two minutes at a temperature of 1150°C under atmospheric pressure conditions. Then the 3C-SiC growth occurred at a temperature of 1250°C where the process pressure was decreased to 100 Torr. The process Si/C and Si/Cl ratios during the growth step were set to be 1.0 and 6.0, respectively. The growth rate dependence on HCl mole fraction and deposition temperature were determined. It was observed that the 3C-SiC deposition rate decreased with increased HCl mole fraction. Atomic Force Microscopy (AFM) analysis was taken in non-contact mode (scan area $5 \mu\text{m} \times 5 \mu\text{m}$) for epitaxial films grown with HCl mole fraction ranging from 0 to 1.0×10^{-4} . An improvement in the surface morphology of the SiC surfaces as the HCl mole fraction increased was observed. This can be verified by a considerable reduction in the surface roughness of the deposited films; roughness values ranged from 23.9 to 2.3 nm RMS for the HCl mole fraction stated above. It was determined that the optimum Si/Cl ratio during this work was 6.0. At this ratio better oriented surfaces with

larger anti phase/micro twin boundaries were obtained with a corresponding minimum surface roughness of 2.3 nm RMS measured. The significant decrease in surface roughness after small increases in HCl mole fraction indicates the benefit of HCl addition to this precursor chemistry were surface morphologies are comparable to 3C-SiC films grown at higher deposition temperatures (1385°C). However, further surface morphology improvement is limited by the anti phase/micro twin boundaries in the 3C-SiC films and film degradation at higher HCl mole fractions where the etching rate appears to exceed the deposition rate. Epitaxial layer characterization via X-ray Diffraction (XRD), Auger Electron Spectroscopy (AES) and Transmission Electron Microscopy (TEM) will be presented along with the experimental results of the growth rate dependence on deposition temperature.

11:20 AM

Q9, Late News

11:40 AM

Q10, Late News

Session R: ZnO Growth: Films and Nanostructures

Thursday AM
June 21, 2007

Room: 141
Location: DeBartolo Hall

Session Chairs: Maria Losurdo, Institute of Inorganic Methodologies and Plasmas; Yicheng Lu, Rutgers University

8:20 AM Student

R1, Growth of Polarity Controlled ZnO Films on (0001) Al₂O₃: *Jinsub Park*¹; Tsutomu Minegishi¹; Seunghwan Park¹; Inho Im¹; Soonku Hong²; Jaewook Lee³; Jeongyong Lee³; Jiho Chang⁴; Meoungwhan Cho¹; Takafumi Yao¹; ¹Institute for Materials Research, Tohoku University; ²Chungnam National University; ³Korea Advanced Institute of Science and Technology; ⁴Korea Maritime University

ZnO has naturally crystal polarity along the c-axis due to crystallize in wurtzite structure. This feature makes the difference of surface morphology, structural properties, and chemical properties. Therefore, the crystal polarity of ZnO films plays an important role in performance of optical devices. In addition, the polarization induced electric fields affect the properties of electronic and optical devices. To date, only a few methods for polarity control of ZnO layers grown on (0001) Al₂O₃ have been achieved,^{1,2} which include the growth of ZnO films with MgO buffer on c-sapphire substrates. In this study, we report the successful polarity control of ZnO films on (0001) Al₂O₃ by using CrN and Cr₂O₃ intermediate layers between ZnO and (0001) Al₂O₃. ZnO layers grown on rock-salt CrN and rhombohedral Cr₂O₃ crystallize in Zn- and O-polar wurtzite ZnO, respectively. Experimental procedures and results are summarized as follows: (1) Zn-polar ZnO are grown on CrN/Al₂O₃ heterostructure by MBE. Rock-salt structure CrN layers are grown by MBE using Cr and nitrogen plasma as sources. TEM studies indicate the ZnO/CrN interface without any oxide layer formation, when Zn beam is exposed onto the CrN surface prior to the growth of ZnO. The epitaxy relationship is determined by RHEED and TEM as follows: ZnO(0001) // CrN(111) // Al₂O₃(0001) and ZnO[2-1-10] // CrN[01-1] // Al₂O₃[10-10]. (2) O-polar ZnO are prepared on Cr₂O₃/CrN/Al₂O₃ heterostructures by MBE, where the Cr₂O₃ layer is formed by oxidation of the CrN surface. The Cr₂O₃ layer is a rhombohedral structure as determined by HRTEM. The epitaxy relationship is as follows: ZnO(0001) // Cr₂O₃(0001) // CrN(111) // Al₂O₃(0001) and ZnO[2-1-10] // Cr₂O₃[10-10] // CrN[01-1] // Al₂O₃[10-10]. (3) Possible interface bonding models are proposed to explain the mechanism for polarity control on rock salt CrN and rhombohedral Cr₂O₃ buffer layers on Al₂O₃(0001). In conclusion, we report a very reliable and reproducible method for the growth of Zn-polar ZnO films and O-polar ZnO films on (0001) Al₂O₃ respectively by using rock salt CrN and rhombohedral Cr₂O₃ buffer as key materials to control the polarities of ZnO films. ¹H. Kato et al., Appl. Phys. Lett. 84, 4562 (2004). ²Y. Wang et al., Appl. Phys. Lett. 87, 051901 (2005).

8:40 AM Student

R2, Lattice Strain Evolution in ZnO Films Grown on MgO/c-Sapphire: *Seunghwan Park*¹; Tsutomu Minegishi¹; Jinsub Park¹; Hiroki Goto¹; Gakuyo Fujimoto¹; Katsuhiko Inaba²; Inho Im¹; Dongcheol Oh³; Soonku Hong⁴; Takashi Hanada⁴; Meoungwhan Cho¹; Takafumi Yao¹; ¹Tohoku University; ²Rigaku Corporation X-Ray Research Laboratory; ³Hoseo University; ⁴Chungnam National University

There is a large lattice misfit of 18.6% between ZnO and c-sapphire, which gives rise to residual strain in a ZnO film. By introducing the MgO buffer to mediate a large lattice misfit, a structure of the ZnO/c-sapphire can be considered by two heterosystems; the ZnO/MgO with 9.3% lattice misfit and the MgO/c-sapphire with 8.1% lattice misfit. This implies that the MgO buffer on c-sapphire as well as the ZnO film on the MgO buffer will undergo reduced misfit strains compared with the case when the ZnO films are grown directly on c-sapphire. Although the insertion of thin MgO buffer in between ZnO and c-sapphire dramatically improves the crystal quality of ZnO films,¹ the evolution of lattice strains during the growth of the ZnO films has not been clarified yet. Therefore, the purpose of this study is to evaluate the lattice strains in ZnO films grown on MgO/c-sapphire by using the plasma assisted molecular beam epitaxy (P-MBE). Experimental results are summarized as follows: (1) Atomic force microscopy (AFM) images of the grown film surfaces and in situ reflection high energy electron diffraction (RHEED) observation have revealed two-dimensional growth features at the initial stage, followed by a gradual transition to three-dimensional growth with increasing the film thickness, which presumably resulted from the strain relaxation. (2) The in-plane lattice spacing evolution of the 10 nm thick ZnO film assessed by RHEED observation during the growth has revealed that the in-plane lattice parameter (aZnO[1-210]) gradually increases above 5.5nm, presumably due to generation of misfit dislocations. Such change of in-plane lattice parameter of ZnO indicates that the critical thickness of ZnO on MgO is 5.5 nm. The determined a-axis lattice parameter of 0.3205 nm during the relaxation process is much smaller than that of strain-free ZnO of 0.3256nm, which indicates the highly compressive strain in the ZnO film. (3) The lattice strains of ZnO thick films with thicknesses ranging from 40 to 2000 nm were evaluated by high resolution X-ray diffraction (HRXRD). Thinner ZnO films show compressive strains however, a change to the broad tensile maximum and the increment relaxation are observed eventually with increasing the thickness. In conclusion, we have elucidated the evolution of lattice strains in ZnO thin films grown on MgO buffer on c-sapphire from the very beginning of the growth to the thick growth. Observed strain evolution can be discussed taking the lattice misfit, thermal stress, and grain formation into account. ¹Yefan Chen, Hang-Ju Ko, Soon-Ku Hong, and Takafumi Yao, Appl. Phys. Lett. 76, 559 (2000).

9:00 AM

R3, Electrical and Optical Properties of MgZnO Films Prepared by Pulsed Laser Deposition: *A. Y. Polyakov*¹; Alexander Belogorokhov¹; N. B. Smirnov¹; E. A. Kozhukhova¹; A. V. Markov¹; Hyunsik Kim²; D. P. Norton³; S. J. Pearton³; Fan Ren²; ¹Institute of Rare Metals; ²University of Florida

Hall effect measurements, the temperature dependence of conductivity, thermally stimulated current, photocurrent relaxations, optical transmission spectra and microcathodoluminescence (MCL) spectra of MgZnO(P) (Mg composition close to 10%) films prepared by pulsed laser deposition and subjected to annealing in argon were studied and compared to the properties of similarly grown and annealed ZnO(P) films. As-grown films, both ZnO and MgZnO, showed n-type conductivity, but the activation energy of conductivity increased from 30-50 meV typical for ZnO to about 80 meV for MgZnO. After annealing at 900°C for 3 minutes for ZnO or for 800°C for MgZnO the apparent conductivity of the films became p-type, with the activation energy of conductivity of 0.1-0.13 eV for ZnO and 0.17-0.19 eV for MgZnO. Thus, residual donors and P acceptors became somewhat deeper when switching from ZnO to MgZnO which could be a manifestation of increased effective mass of electrons and holes in the ternary solid solution. Both ZnO and MgZnO samples showed a prominent persistent photoconductivity with threshold energy for optical excitation close to 2.8 eV, the waveform of relaxation reasonably described by the stretched exponents model, a relaxation time of hours even at room temperature and a high activation energy for these relaxation times. Annealing did not change the character of persistent conductivity but measurably reduced its

magnitude. It also had a strong effect on MCL spectra of the films increasing the intensity of the bandedge luminescence and decreasing the intensity of the defect bands in the green and red regions of the spectra. The work at IRM was supported in part by a grant from the Russian Foundation for Basic Research (RFBR grant # 06-02-08226, 06-02-16555).

9:20 AM Student

R4, Optical and Structural Characterization of ZnO/Mg_xZn_{1-x}O Quantum Wells Synthesized by Pulsed Laser Deposition (PLD): *Willie Bowen*¹; Weiming Wang¹; Emine Cagin¹; Jamie Phillips¹; ¹University of Michigan

The wide-bandgap II-VI wurtzite semiconductor ZnO and its wurtzite alloy, Mg_xZn_{1-x}O ($x \leq 0.3$), are promising candidates for the realization of ultraviolet (UV) light emitting devices and detectors. The characteristics of heterojunctions and quantum-confined structures based on ZnO/MgZnO are only in the beginning stages of exploration, but will serve as the basis for the future electronic and optoelectronic devices based on these materials. In this work, we investigate the optical properties of ZnO/Mg_xZn_{1-x}O quantum well (QW) structures grown on c-plane sapphire substrates by pulsed-laser deposition with bandgap offsets ≤ 0.25 eV. A blueshift in the low-temperature photoluminescence (PL) of the QWs revealed quantum confinement as a function of ZnO well widths ranging from 30 to 70 Å. X-ray diffraction (XRD), PL emission peak, and transmission electron microscopy (TEM) are used for crystal structure analysis, determination of Mg content in the barrier layers, and surface roughness between the heterostructure layers, respectively. The role of annealing temperature dependence and temperature-dependent PL on the emission mechanism of the ZnO/MgZnO system will be discussed.

9:40 AM

R5, Effect of Buffer Layers on Mg_xZn_{1-x}O Films Grown on c-Sapphire by P-MBE - A Comparison Study: *Zahra Vashaei*¹; Tsutomu Minegishi¹; Takafumi Yao¹; ¹Tohoku University

In the recent years, there has been much interest in ZnO and ZnO based alloys and their heterostructures due to wide band gap energy of over 3.3 eV, which makes them promising candidates for application in blue and ultraviolet light-emitting devices. Amongst the ZnO based alloys, Mg_xZn_{1-x}O, which is realized by alloying MgO with ZnO, exhibits the same material advantages as pure ZnO. By varying the Mg composition, the band gap can be tuned from 3.3 to 5.4 eV,¹ which is a significant property of Mg_xZn_{1-x}O for application as a proper barrier for ZnO in ZnO/MgZnO superlattice structures. Mg_xZn_{1-x}O layers can possess two different crystal structures, rock salt-cubic or hexagonal-wurtzite depending on the Mg content. However, the large crystal structure dissimilarity of ZnO (wurtzite) and MgO (rock salt) leads to instability of Mg_xZn_{1-x}O phase between $0.33 \leq x \leq 0.6$.² It is worth to remind that Mg_xZn_{1-x}O crystal structure can be affected by lattice misfit and crystal structure of buffer layer or substrate. In order to improve the crystal quality and control the growth direction as well as crystal structure of Mg_xZn_{1-x}O thin films, use of proper buffer layer plays an indispensable role. In this letter we will report on a comparison study of growing Mg_xZn_{1-x}O thin films using two different templates, MgO/ c-sapphire and ZnO/ MgO/ c-sapphire. For this purpose we investigated the crystal structure variation of Mg_xZn_{1-x}O films grown by plasma-assisted molecular beam epitaxy (P-MBE) over a wide composition range of $0.0 < x < 1.0$. Reflection high-energy electron diffraction (RHEED), high-resolution transmission electron microscopy (HRTEM), high-resolution x-ray diffraction (HRXRD), and atomic force microscopy (AFM) were employed to characterize the layers. XRD results demonstrate that solid solubility of MgO in ZnO and vice versa can be affected by the template crystal structure. HRTEM results reveal that the rock salt-Mg_xZn_{1-x}O layers grow along the [001] direction on ZnO/ MgO/ c-sapphire templates whereas they take [111] direction when grow on MgO/ c-sapphire templates. The results indicate that using ZnO/ MgO/ c-sapphire templates growth of wurtzite Mg_xZn_{1-x}O layers with high Mg concentration ($x > 0.5$) are feasible however introducing a thin MgO buffer layer can preserve growth of rock salt-Mg_xZn_{1-x}O layers with low Mg concentration. Further discussion will be presented at this work. ¹T. Makino, Y. Segawa, M. Kawasaki, H. Kinuma, *Semicond.Sci.Technol.* 20, S78 (2005). ²A.Ohtomo, A.Tsukazaki, *Semicond. Sci. Technol.* 20, S1 (2005).

10:00 AM Break

10:20 AM

R6, Late News

10:40 AM

R7, Late News

11:00 AM

R8, Selective Growth of Single ZnO Nanorod: *Kazumuki Yamamoto*¹; Kazuhiko Amano¹; ¹Chiba University

We have already reported the selective growth of zinc oxide nanowire bundles on the patterned Cu underlayer or at the small pit of the substrate. "Single nanowire at the single site" has been our ultimate goal. In this paper, we report the experimental evidence that single ZnO nanorod or nanowire has been selectively grown just at a site of nano-pit fabricated at the surface of a substrate. The ZnO nanorods or nanowires were synthesized by a reactive evaporation method on SiO₂/Si or Cu-metalized SiO₂/Si substrate with a metal Zn source. Oxygen gas was introduced through a nozzle placed very near to the substrate. This configuration enables the Zn metal to be oxidized. Typical substrate temperature was 500C, and ambient O₂ pressure was 4×10^{-4} Torr. These values are fairly low compared with other methods. Diameter of the nanorods or nanowires obtained was 10 ~ 200 nm and the length was ranged from 100 nm to 10 μm. Crystallization of the products was confirmed by x-ray diffraction. The results of low temperature photo luminescence measurements show clear near-band-edge emission of ZnO, which may be identified as the emission of an exciton associated with the neutral donor, (D⁰, X). The nano-pit array was fabricated by electron beam lithography and reactive ion etching. Typical diameter and depth of the pits were 50 nm and 100 nm, respectively. When the evaporation was carried out on these processed substrates, single or a few nanorods or nanowires were selectively grown just at the site of nano-pits and no other products were found around the pits. This result must open a new vista for the applications of ZnO nanostructures, such as field emission displays, nanomachines and so on.

11:20 AM Student

R9, Optical Properties of ZnO Nanostructures: Sang Hyun Lee¹; Takenari Goto¹; Hiroshi Miyazaki²; Meoung-Whan Cho³; *Takafumi Yao*⁴; ¹Center for Interdisciplinary Research, Tohoku University; ²Department of Applied Physics, Tohoku University; ³Institute for Materials Research, Tohoku University; ⁴Center for Interdisciplinary Research, Institute for Materials Research, Tohoku University

We will present optical properties of various ZnO nanostructures including nanowires and nano multipods. Room temperature photoluminescence (PL) spectra of ZnO nanostructures under a weak excitation regime are dominated by free exciton emission owing to the large exciton binding energy. The excitonic emissions from the nanostructures are compared with those from thin films and bulk crystals with special attention being paid to the temperature dependence of PL properties. At low temperatures, the line width of bound exciton emissions from ZnO nanowires is as narrow as ~1.9 meV, which is comparable with the value obtained from bulk ZnO. The activation energy is estimated from a plot of the bound exciton emission intensity against temperature for ZnO nanowires. With increasing excitation intensity, the "P" emission due to exciton-exciton scattering emerges and eventually dominates the PL spectra. A plot of emission intensity against excitation intensity shows a threshold behavior indicating stimulated emission from the ZnO nanostructure. We found that micro PL investigation on single multipod under strong excitation conditions reveals lasing of the "P" emission associated with longitudinal modes. A possible optical cavity for lasing from the ZnO multipod is investigated based on theoretical consideration.

11:40 AM Student

R10, Integrated ZnO Nanotips on GaN Light Emitting Diodes for Enhanced Emission Efficiency: *Jian Zhong*¹; Hanhong Chen¹; Gaurav Saraf¹; Yicheng Lu¹; C. K. Choi²; J. J. Song²; H. Shen³; ¹Rutgers University; ²ZN Technology; ³Army Research Laboratory

Due to the narrow escape cone in high refractive index GaN, the external quantum efficiency of a conventional planar structure nitride LED is significantly lower than the internal quantum efficiency. Many research efforts are being made to improve the light extraction efficiency in GaN LEDs, such as surface roughing, forming photonic crystals on the top layer. Other techniques include light output coupling through surface plasmons

or corrugated Bragg grating, to convert wave-guided modes into free-space modes. Since the manipulation of a thick p-type GaN layer is undesirable due to its high resistivity, flip-chip bonding and laser lift-off technologies have been used to make an n-side-up device. These approaches significantly increase the complicity of the GaN LED fabrication. ZnO is emerging as a promising wide bandgap semiconductor for UV optoelectronics. Ga doped ZnO (GZO) film has been used as transparent conductive oxide (TCO) contact to p-GaN. Single crystalline ZnO 1-D nanostructures have been grown on various substrates such as GaN, Si and glass by MOCVD, which possess excellent optical properties. In this work, we report the integration of ZnO nanotips with GaN for novel LED devices. Two types of ZnO nanotips/GaN LED devices are fabricated: (i) n-ZnO nanotips/p-GaN heterojunction LEDs; and (ii) ZnO nanotips on top of a GaN LED for enhanced light extraction efficiency. I-V characteristics and electroluminescence properties of a heterostructure p-n junction consisting of n-type ZnO nanotips grown on p-type GaN are present. In addition, enhanced light extraction efficiency is demonstrated by integrating ZnO nanotips on top of a GaN LED. The device is composed of a GaN LED with a top electrode of a GZO layer, and ZnO nanotips for light extraction. Two-step MOCVD growth technique was developed to sequentially grow GZO film and ZnO nanotips on GaN. GZO layer is first grown on p-GaN of a GaN LED, which is used as the metal contact to p-GaN and optically transparent window for the blue emission. ZnO nanotips with a height of ~ 400nm are then grown on GZO coated GaN as a light extraction layer. No nanolithography is required to form the nanotips array. Therefore, it is suitable for low cost fabrication. Structural and optical properties of the nanotips grown on GZO/GaN were investigated with XRD and PL. LIV and emission spectra of the LEDs were studied. The light output power of a ZnO nanotips/GZO/GaN LED exhibits 1.7 times enhancement at a forward current of 20mA, in comparison with a conventional Ni/Au p-contact GaN LED and a reference GZO/GaN LED without nanotips. Our results promise the integration of ZnO nanotips with GaN based optoelectronic devices using state-of-the-art epitaxial growth technology. This work has been supported by NSF under grant CCR-0103096, and by ARO under grant #W911NF-05-C-0023.

Session S: Metamorphic Materials: Characterization and Devices

Thursday PM
June 21, 2007

Room: 126
Location: DeBartolo Hall

Session Chairs: Steven Ringel, Ohio State University; Ya-Hong Xie, University of California, Los Angeles

1:30 PM Student

S1, Formation of Interfacial Misfit Array for AlSb on Miscut Si Substrate: Shenghong Huang¹; Ganesh Balakrishnan¹; Arezou Khoshakhlagh¹; Peng Li¹; L. Dawson¹; Diana Huffaker¹; ¹University of New Mexico

The monolithic growth of III-V materials on Si offers several desirable features such as efficient use of the integrating platform and reduced processing complexity. However, mismatch in lattice constant, thermal expansion coefficient and process temperature prevents the establishment of a stable and repeatable production process. Our method for monolithic III-V growth on Si is different from previously reported work due to the unique growth mode of AlSb on 5° miscut Si through 90° interfacial misfit (IMF) array formed at the interface. The IMF array has been shown to significantly reduce defect density in the growth of AlSb on Si(100) and has resulted in the demonstration of optically pumped edge-emitters and VCSELs along with superluminescent light emitting diodes. However the presence of anti-phase domains in this growth mode has proven to be detrimental to the performance of electrically injected lasers. Previous attempts to form the IMF array on miscut Si substrates (3° miscut towards 110) has failed and resulted in a significantly higher threading dislocation density. However, with the use of a 5° miscut substrate, cross-section TEM images indicate a high quality IMF array at the AlSb/Si interface. Theoretically, if the step

length L is very close to the dislocation spacing S, then the dislocations may be confined at the step edge and form a type of edge dislocation. For AlSb-Si material system, $S = 34.6 \text{ \AA}$ and step height $h = 3.58 \text{ \AA}$, therefore 5° misorientation can provide the closest step length L to this value. According to the theoretical calculation, the double-step height on Si(100) surface is close to the step height. Thus, we attribute the success of AlSb growth on Si with a 5° miscut surface to both the step doubling-atom mechanism in combination with the strong AlSb atomic bond. The misfit array and resulting bulk materials have been analyzed carefully using TEM images. Careful examination of the atomic lattice surrounding the interfacial misfits using cross sectional HRTEM image shows that the Burger's vector, i.e., $a/2[110]$, lies along the interface and identifies this misfit as 90° pure edge type. The misfit separation, measured to be ~ 3.46 nm, corresponds to exactly 8 AlSb lattice sites grown on 9 Si lattice sites. The identical misfit arrays have been observed along both [110] and [1-10] directions, which shows that there is a 2D 90° pure edge dislocation array at the AlSb/Si interface. We also characterize our material using PL, HR-XRD and analyze residual domain densities using HR-SEM and AFM. We conduct extensive plan-view TEM investigations of the growth to account for threading dislocation densities and we also compare the dislocation density on AlSb/Si (5° miscut) with similar growths on Si(100) substrates.

1:50 PM Student

S2, Preparation and Characterization of Relaxed Si_{0.08}Ge_{0.92} Surfaces for MBE Growth on Virtual SiGe Substrates: Katherine Dykes¹; M. Brenner¹; Sarah Bertke¹; C. Dohrman²; Eugene Fitzgerald²; Steven Ringel¹; ¹Ohio State University; ²Massachusetts Institute of Technology

The ability to integrate III-V materials onto Si continues to be of great interest with respect to many advanced applications such as next generation high performance III-V photovoltaics. One successful approach uses relaxed, step-graded buffers of Si_xGe_{1-x} from 0 to 100% Ge to create "virtual" Ge substrates that are closely lattice-matched to GaAs. Using Molecular Beam Epitaxy (MBE), a variety of III-V heterostructure devices, such as GaInP/GaAs solar cells, have been incorporated onto Si via a Ge virtual substrate. However, this approach is not necessarily limited to 100% Ge. Any composition of Si_xGe_{1-x} could potentially be used as a "virtual" substrate for growth of novel III-V device structures spanning a much wider range of lattice-constants. An important first step in reaching such a goal is the preparation of a smooth and contaminant free substrate surface for growth initiation. Extensive literature exists on cleaning and preparing both Si and Ge surfaces, but this knowledge does not directly translate into an efficient process for MBE preparation of Si_xGe_{1-x}. Thus, it is important to understand the procedures necessary to effectively prepare Si_xGe_{1-x} surfaces for III-V epitaxy. This study uses a particular composition of Si_xGe_{1-x} (Si_{0.08}Ge_{0.92}), selected out of a series of samples grown with compositions from 50-100% Ge. This composition was chosen since its direct and indirect bandgaps are of interest for low bandgap solar cell applications. Using traditional Si and Ge cleaning procedures as reference points, a variety of methods were used to prepare the Si_{0.08}Ge_{0.92} substrate. These methods included ex-situ wet-chemical treatments and surface passivation to UV-ozone and in-situ desorption of a sacrificial oxide layer. Samples were systematically evaluated as a function of clean/etch conditions using x-ray photoelectron spectroscopy (XPS) and electron microscopy. XPS results confirmed the expectation that the Si_{0.08}Ge_{0.92} oxide formed was two-phase (consisting of separate SiO₂ and GeO₂ components). While the GeO₂ component fully desorbed at temperatures above 500°C thermocouple, the SiO₂ component remained until a temperature of 850°C thermocouple was reached. However, results from energy dispersive analysis of x-rays (EDAX) indicated that the high temperatures affected the composition of the surface. Potential changes in composition are worrisome given the goal of precisely tuning the lattice-constant for device growth and applications. Therefore, wet-chemistry treatments and surface passivation were further explored as a low-temperature alternative for oxide removal. Various ratios of HF:DI mixtures were used and while ratios at or in excess of 1:10 were found to effectively remove the oxide but also resulted in roughening of the Si_{0.08}Ge_{0.92} surface. Currently, we are performing surface compositional studies and these results will be correlated with the XPS data from various cleaning procedures in order to understand the necessary conditions for preparing mixed SiGe surfaces for subsequent III-V heteroepitaxy.

2:10 PM Student

S3, Strain Induced Surface Reconstruction on Sb/GaAs(001): *Jessica Bickel*¹; N. A. Modine²; Chris Pearson³; Joanna Mirecki Millunchick¹; ¹University of Michigan-Ann Arbor; ²Sandia National Laboratories; ³University of Michigan-Flint

The surface reconstruction of compound semiconductors has an important influence on the growth of thin films of these alloys, affecting both compositional uniformity and the morphology of these films. It has been suggested that strain also influences surface reconstructions. We have examined thin layers of the surfactant Sb on GaAs(001) through both experiment and Density Functional Theory (DFT) to explore the role of strain in the surface reconstruction of Sb/GaAs(001). For films of thickness, h , where $0.8h=1.7$ monolayers (ML) the film displays a 2×4 reconstruction according to Reflection High Energy Electron Diffraction (RHEED), and a mixed surface reconstruction according to Scanning Tunneling Microscopy (STM). The mixed surface reconstruction is comprised of an $\alpha 2(2 \times 4)$ which is not usually seen in GaSb films, but is commonly seen in Sb-capped GaAs, and an $\alpha(4 \times 3)$, one of the thermodynamically stable bulk GaSb reconstructions proposed by Barvosa-Carter *et al.* The $\alpha 2(2 \times 4)$ appears predominately on terraces or in the center of islands while the $\alpha(4 \times 3)$ appears predominately at the step edges, and the critical size of an island before the $\alpha 2(2 \times 4)$ appears is $30 \pm 10 \text{ nm}^2$. This suggests that the Sb first incorporates into the surface in a $\times 3$ reconstruction, then transitions quickly to a $\times 4$ reconstruction, presumably due to strain. The $\alpha 2(2 \times 4)$ better relieves strain due to the additional height and the lack of interaction of dangling bonds. Density Functional Theory (DFT) confirms that strain is playing a large part in the mixed reconstruction surface. GaSb surfaces show a large shift in surface stability of reconstructions between the GaSb lattice parameter and the GaAs lattice parameter, with the (2×4) reconstruction becoming more energetically stable as the surface is strained. This corresponds with the appearance of the $\alpha(4 \times 3)$ at terrace edges because the lattice parameter is able to relax.

2:30 PM

S4, Interfacial Structure of Tilted InAs Islands on GaAs: *Xueyan Song*¹; Thomas Kuech¹; Susan Babcock¹; ¹University of Wisconsin-Madison

The potential for use of the “ 6.1 \AA ” compound semiconductors (InAs, GaSb, InSb) in optical and electronic device applications has driven interest in their epitaxy on GaAs. Fabrication of device quality films on this 7% lattice-mismatched substrate requires the development growth strategies that minimize defect incorporation and better understanding of how mismatch strain is accommodated in largely lattice mismatched compound semiconductors. The microstructures observed in InAs on [100] oriented GaAs suggest that the relaxation mechanism evolves with increasing island size (G. Suryanaryanan, Khandehar, Kuech and Babcock, EMC 2006). Specially, orientation imaging studies reveal in isolated islands with micron-scale lateral dimensions a distinct domain microstructure in which the InAs is tiled relative to the GaAs in a characteristic pattern. In this study, transmission electron microscopy (TEM) imaging and diffraction techniques were used to characterize the tilt in the vicinity of the interface. High resolution TEM (HRTEM) imaging was used to investigate the interface structure as a function of local tilt. The TEM studies revealed five domains in islands with lateral dimensions of approximately one micrometer. The center of the island was aligned with the GaAs substrate. Each of the other subsections was tilted up to four degrees relative to the substrate, mirroring the orientation imaging results for islands of the same size range that samples the top ~ 30 nm of the island. These results confirm that the tilt is established at the interface rather than within the island volume. HREM imaging of the interfacial dislocation network revealed a change in the make-up of the mismatch dislocation array from side to side across the island. Near the center of the island, where the InAs was aligned crystallographically with the GaAs, the 60° dislocations present occurred in pairs to produce a net Burgers vector in the [100] direction of zero. Near the island's outer edges, the 60° dislocations in the interface all had Burgers vector, rendering a non-zero burgers vector density in the [100] direction that was oriented as needed to produce the crystal tilt measured above the array. These results are consistent with a model proposed by Spencer and Tersoff ([1].B.J. Spencer, and J. Tersoff, Appl. Phys. Lett. 77 (1997) 2533.[2].B.J. Spencer, and J. Tersoff, Phys. Rev. B63 (2001) 205424) and with the systematic pattern of tilt observed in films. Both the model and the experimental results suggest that film quality is improved when the grown

conditions favor island coalescence at small island size. This observation may explain the efficacy of nucleation layers in improving film quality.

2:50 PM Student

S5, Lattice-Engineering for Monolithic Visible Yellow-Green Light Emitters: *Michael Mori*¹; Eugene Fitzgerald¹; ¹Massachusetts Institute of Technology

III-V materials systems for high-brightness light emitting diodes (HBLEDs) and laser diodes (LDs) in the blue and red regions of the visible spectrum are well established, however materials for green emission lag behind in performance. Because of its large bandgap (up to 2.5eV), the quaternary alloy AlInGaP offers promise as a green light emitting material, however lattice-match constraints have traditionally limited it to use at the GaAs lattice constant. Here, the bandgap reaches only 2.3eV and the widest direct bandgap material has relatively high Al content (near $\text{Al}_5(\text{In}_5\text{Ga}_5)_5\text{P}$), making devices susceptible to performance degradation from O-related defects. More attractive alloys of AlInGaP exist at smaller lattice constants where the direct bandgap is wider with less or no Al and the indirect bandgap is much larger. The greater electrical and optical confinement provided by these materials will shorten wavelength, improve efficiency and enable LDs with record low wavelength. Thus, effectively engineering the lattice mismatch between these compositions of AlInGaP and commonly available substrate materials (GaAs, GaP, Si) is a key technological hurdle to attaining green HBLEDs and LDs. Integration of AlInGaP on large substrates (6” and above) will reduce optical device production costs drastically, to less than that of sapphire-based III-N devices. Achieving high-efficiency light emission on a monolithically integrated platform will also enable numerous high volume applications in printing, imaging, and projection. We focus on AlInGaP alloys with lattice parameters intermediate to GaP and GaAs, at 5.57 \AA , close to the direct-indirect transition for the material. Via MOCVD, we fabricated GaAsP metamorphic compositionally graded buffers which will be used as virtual substrates for green light emitting devices. Previously, we showed that replacing As with P in GaAsP/GaAs relieved tensile strain with very little increase in threading dislocation density (TDD). The final TDD of these structures was near $1 \times 10^6 \text{ cm}^{-2}$, orders of magnitude lower than previous work. The graded buffers were also very thin compared to previous GaAsP work (~ $8 \mu\text{m}$ vs. $20\text{-}50 \mu\text{m}$), but further reduction in thickness resulted in severe cracking of the films. We now report that by grading compressively (replacing P with As in GaAsP/GaP), we maintained the extremely low TDD and complete relaxation achieved in our previous work while we reduced the thickness of the entire structure to $1.3 \mu\text{m}$ with no crack formation. AFM studies showed that the tensile and compressive graded buffers have similar RMS roughness (5.9nm and 6.1nm, respectively, in a $40 \mu\text{m}$ square scan). Non-optimized InGaP-based strained QW heterostructures on these thin virtual substrates demonstrate strong room temperature photoluminescence at 570nm (yellow-green), but require careful engineering of the InGaP/GaAsP interface to avoid defect nucleation. Incorporation of metamorphic buffers in commercial production is quite feasible with these thin structures.

3:10 PM Break

3:30 PM Student

S6, Enhancement-Mode Metamorphic InAlAs/InGaAs HEMTs on GaAs Substrates by MOCVD and Plasma Treatment: *Chak Wah Tang*¹; Haiou Li¹; Kevin Chen¹; Kei May Lau¹; ¹Hong Kong University of Science and Technology

MHEMTs have been successfully developed and geared for commercialization using MBE technique. Metamorphic technology by MOCVD has not been demonstrated with similar success, particularly with device results. We have developed a multi-layered buffer with high resistivity, leading to good device performance. This sets the stage for potential MHEMT manufacturing by MOCVD. Adopting a CF_4 plasma treatment process we developed for the III-nitride system, we demonstrated enhancement-mode metamorphic InAlAs/InGaAs HEMTs grown by MOCVD on GaAs substrates. Shifting of the threshold voltage from negative (depletion mode) to zero (enhancement mode) can be adjusted with the process parameters. The plasma process also provides a side benefit of reducing the leakage current of the device. Metamorphic $\text{In}_{0.51}\text{Al}_{0.49}\text{As}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ HEMTs were grown on 4-inch (001) oriented semi-insulating GaAs substrates using an Aixtron AIX-200/4 MOCVD system. The growth temperature of the first InP metamorphic

buffer layer was varied from 450 to 600°C. Another low-temperature (LT) InP: C layer grown at 500°C serves as a high resistivity buffer to isolate the active layers from the conductive buffer. This is followed by a composite LT, high resistivity InAlAs and a HT (600°C) 100nm-thick InAlAs. The δ -doped MHEMT active layers, were grown at a substrate temperature of 650°C. Room temperature Hall mobility of 2DEG is over 7000cm²/V-s with sheet carrier densities larger than 4.8x10¹²cm⁻². Device mesa was formed by wet selective etching and followed by source-drain ohmic contact formation using Ni/Ge/Au/Ge/Ni/Au. The non-alloyed Ohmic Contact resistance R_c was about 0.1Ω-mm. After the D-mode gate recess etching, the gate region of E-mode devices was treated by CF₄ plasma in a PECVD system with different RF power and time. The gate electrode and the plasma treated gate recessed region were self-aligned. Then, Ti/Pt/Au gate metal was formed by e-beam evaporation and lift-off. After the gate recess regions were treated by CF₄ plasma with RF power 150W for 150s, the threshold (V_{th}) of devices shifts in the positive direction, from -0.7V to -0.05V. The peak gm was 315mS/mm for the D-mode HEMT and 305 mS/mm for the E-mode, respectively. The maximum drain current (I_{max}) was 330mA/mm for D-mode and 220mA/mm for E-mode mHEMTs, respectively. Measured by AFM, the thickness of the InAlAs barrier layer was found to be reduced by 0.6nm after CF₄ plasma treatment, suggesting the threshold shift was not a result of the etched barrier layer. Another side benefit after CF₄ plasma treatment was that the reverse-bias gate leakage currents were significantly reduced, up to two orders of magnitudes at V_g=-3V. The current-gain cutoff frequency f_T and the maximum available gain f_{max} were estimated by extrapolating at -6dB/octave for the D-mode mHEMTs. As shown in Fig.6, f_T is 17.9GHz and f_{max} is 80GHz.

3:50 PM Student

S7, Simulations of GaP and GaAlAs as the High Band Gap Cell for Multijunction High Efficiency Solar Cell Applications: *Charles Allen*¹; Jerry Woodall¹; Jong-Hyeok Jeon¹; ¹Purdue University

The dominating challenge facing the semiconductor solar industry is finding an economically sound solution. There are two leading methodologies; very low cost thin film cells of moderate efficiencies, e.g. >15%; and ultra high efficiency multijunction cells utilizing an optical concentrator system. Our group is committed to the latter approach. For tandem cell stacks, the most pressing issue is finding a material with an energy gap of about 2.4 eV and properties suitable for solar cells. Having a top cell with these properties is necessary to manufacture a cell capable of 50% efficiency. There are several groups investigating AlGaInP and InGaIn alloys for the top cell. Our group has focused on both GaP and Al_xGa_{1-x}As alloys for x values between 0.5-0.6. GaP has both advantages and disadvantages for top cell application. The disadvantages are two-fold. First, the indirect gap is 0.14eV less than the desired 2.4 eV. This means an optimized cell can be expected to have a Voc of 1.8-1.9 volts, lower than the 2.0-2.1 expected from a 2.4 eV material. The second issue results from the indirect nature of the 2.26eV gap; thick layers with good minority carrier diffusion lengths are needed to absorb and collect the solar spectrum for energies above the indirect gap. Fortunately, the direct gap of GaP is 2.76 eV. To collect all solar photons above the direct gap, only 2 microns of material is needed. The pass-through of unabsorbed photons with energies between 2.26 and 2.76 is not a significant loss. Al_{0.6}Ga_{0.4}As has similar virtues with a direct edge only 0.15 eV above the indirect edge. Additionally, it is lattice matched to GaAs. However, the indirect gap is 2.1 eV, resulting in an even lower Voc than GaP. In this talk we will present rigorous simulations of efficiencies for GaP and AlGaAs as justification for these materials as the top cell of a tandem stack. For example, for GaP with realistic electron and hole minority carrier lifetimes, only 10 microns of epilayer thickness is needed to give a 50+% conversion efficiency of the AM 1.5 spectrum that GaP can absorb. If this same spectrum were incident on an optimized GaAs cell, the efficiency would only be 32%. Even worse, for Si this spectrum would produce an efficiency of only 18.5%. This is in contrast to a Si cell with an expected efficiency of 28% for the AM1.5 spectrum that silicon can absorb.

4:10 PM Student

S8, Selective Characterization of Deep Levels Defects within Sub-Cells of Dual Junction III-V Solar Cells Grown on Metamorphic SiGe Substrates: *Maria Gonzalez*¹; Andrew Carlin¹; Robert Walters²; Scott Messenger²; Jeffrey Warner²; Justin Lorentzen²; Carl Dohrman³; Eugene Fitzgerald³; Steven Ringel¹; ¹Ohio State University; ²U.S. Naval Research Laboratory; ³Massachusetts Institute of Technology

Integration of III-V photovoltaic devices onto Si is of particular interest for space applications where the lower mass density yet higher mechanical strength of Si when compared to other conventional substrates such as GaAs or Ge, allows a considerable increase in specific power output (W/kg) without a significant reduction in area power density (W/m²). Recently, the use of Si_{1-x}Ge_x compositionally step graded buffers, along with precise III-V/Si interface control, has been established as an effective way to integrate the two material systems. Among other optoelectronic devices, single GaAs/SiGe [1] and dual In_{0.49}Ga_{0.51}P/GaAs/SiGe [2] high performance solar cells have already been demonstrated. However, the presence of a low but non-negligible concentration of threading dislocations generates a need to assess their impact on the detailed electronic properties of these structures to aid continued advancement of this technology. To date, deep level studies have been performed in single junction GaAs/SiGe [3] and InGaP/SiGe under different radiation environment conditions. Though this information serves as a baseline for understanding basic material properties of the separate constituent layers of the more complex multijunction structures, the presence and properties of deep levels within complete InGaP/GaAs/SiGe multijunction structures needs to be understood to completely assess the behavior of such devices in space. In this work, we investigate deep levels present in complete In_{0.49}Ga_{0.51}P/GaAs/SiGe dual junction structures and analyze the correlation to device performance. For that purpose, p-n In_{0.49}Ga_{0.51}P/GaAs dual junction structures, grown by Molecular Beam Epitaxy (MBE) on SiGe virtual substrates, were processed to enable selective characterization of deep levels present within individual InGaP and GaAs sub-cells of the dual junction structure. Direct comparisons were made to the same structure grown on GaAs substrate to discern the effects of residual threading dislocations. Preliminary results showed one dominant majority carrier electron trap in the bandgap of the GaAs n-type base layer of the bottom sub-cell of the In_{0.49}Ga_{0.51}P/GaAs structure, located at E_c-0.42eV, and three majority carrier electron traps at E_c-0.28eV, E_c-0.50eV and E_c-0.80eV in the n-type InGaP base layer of the top sub-cell. The deep level activation energies and concentrations, in all cases below 1x10¹⁴cm⁻³, closely agree with studies in individual GaAs/SiGe [3] and InGaP/SiGe layers indicating excellent reproducibility of material quality in the more complex dual junction structures. Additional experiments performed on the individual InGaP layers showed that under minority carrier injection conditions the level located at E_c-0.80eV also allows transitions from the valence band, suggesting its role as a strong recombination-generation center that can impact dark current and voltage loss in these devices under operation. A systematic comparison of defect properties in these structures will be presented, including results of our ongoing proton radiation experiments currently being performed on the dual junction structures on SiGe.

4:30 PM Student

S9, GaInAs p-Channel HFETs Using Step-Graded AlInAs Metamorphic Buffers: *Mike Morse*¹; Inho Yoon¹; Changhyun Yi¹; April Brown¹; ¹Duke University

Complementary heterostructure field effect transistors (HFETs) have the potential to produce high-speed, low-power ICs. The performance of the p-channel HFET (pch-HFET) must be optimized to achieve this goal. We have investigated the use of an AlInAs step-graded metamorphic buffer to grow high indium content pch GaInAs HFET materials. The metamorphic approach relaxes some of the constraints imposed on epitaxial growth by the substrate by creating a pseudosubstrate of appropriate lattice constant, while controlling strain relaxation to maintain a low threading dislocation density and provide a suitable growth surface. All samples were grown by solid source molecular beam epitaxy (MBE) in a Riber 2300 system equipped with valved cracker source for As. Growth for all samples was initiated with a lattice matched layer of Al_{0.478}In_{0.522}As at T_s = 480°C. Subsequently a step-graded metamorphic buffer was grown up to a composition matching the desired composition of the channel layer. We targeted GaInAs channels with 70, 80,

and 90% In. HFET device structures were grown on top of the metamorphic buffer, consisting of a 20nm GaInAs channel, 2nm AlInAs spacer layer, 8nm Be doped to $3 \times 10^{18} \text{cm}^{-3}$ acceptor layer, 20nm AlInAs Schottky layer, and 5nm Si doped to $6 \times 10^{18} \text{cm}^{-3}$ GaInAs cap layer. An additional sample consisting of only an AlInAs metamorphic buffer was grown to verify that the buffer was insulating and therefore suitable to act as a pseudo-substrate for subsequent device layer growth. High resolution x-ray diffraction reciprocal space mapping (HRXRD RSM) was used to characterize the structural quality, strain relaxation, and composition of each structure. The hole sheet charge density and mobility were measured by room-temperature Hall effect measurements on Van der Pauw type samples with contacts formed by annealing In dots. Surface morphology was measured using a Digital Instruments Dimension 3100 Atomic Force Microscope (AFM) in tapping mode. We observe an unexpected decrease in hole conductivity as the indium content is increased from 508 cm^2/Vs for the 70% indium structure to 128 cm^2/Vs for the 80% indium structure to n-type conductivity in the 90% indium structure. This is attributed to a decreasing efficiency of dislocation management by the metamorphic buffer as the indium content is increased based on the dislocation structure suggested by surface morphology. Further work to improve the metamorphic design for the higher indium content will build upon our promising result for our $\text{Ga}_{0.3}\text{In}_{0.7}\text{As}$ structure.

4:50 PM Student

S10, Growth, Fabrication, and Characterization of an InGaN/GaN Solar Cell by MBE: *Kristopher Matthews*¹; Xiaodong Chen¹; William Schaff¹; Lester Eastman¹; ¹Cornell University

Indium-nitride materials, due to their extensive band gap coverage of the solar spectrum, have great potential as solar cell materials. Due to the remarkable range of band gap tuning with respect to In concentration, layers of varying composition can be stacked to maximize absorption of the solar spectrum. In addition, the mechanical durability and thermal tolerance of InN has made it ideal for integration into solar concentrator arrays. By utilizing concentrator technology, less material needs to be produced, power can be centralized to a grid, and thus energy and financial costs can be reduced. Obstacles to InN cell development include lattice mismatched crystal growth, consistent p-type doping and surface electron accumulation. We have demonstrated a functioning solar cell made from GaN and aim to duplicate this success with an InGaN cell to take advantage of the aforementioned material properties. MBE-grown films of GaN on sapphire substrates were processed into 1 mm x 1 mm solar cells. The films consisted of a 1 μm n-type layer (of carrier concentration $3 \times 10^{19} \text{cm}^{-3}$), followed by a 350 nm intrinsic layer, and then a Mg-doped 90 nm p-type layer ($2 \times 10^{18} \text{cm}^{-3}$ carrier density) on top. Correspondingly, lithography steps were performed on each layer to produce Ni Au ohmic p-contact pads resting atop the mesas, surrounded by a Ti Al Mo Au n-contact pads for the devices. The prototype cells consisted of cells and diodes of varying size to determine their effect on solar cell device performance. IV curves indicated that the GaN cells had low parasitic series resistance (0.12 $\Omega\text{-cm}^2$). Contact resistances of 74 $\Omega\text{-mm}$ and 0.2028 $\Omega\text{-mm}$ for p- and n- contacts, respectively, were measured for the GaN cell. Upon illumination by a 325 nm laser, a peak power output of 20 mWcm^{-2} and clear photo-response can be observed via the IV curve shift. The device performance is represented by a fill factor of 61% and 2.5 V turn-on voltage. The same process was utilized to produce an all-InGaN cell (20% In composition) on a GaN buffer. Contact resistances of 1565 $\Omega\text{-mm}$ and 0.3166 $\Omega\text{-mm}$ were found for p- and n- contacts, respectively, for InGaN. Strong electroluminescence is observed at 550nm. Photovoltaic efficiency is significantly smaller than observed for GaN. Leakage current under forward bias is seen in a softer I-V turn-on characteristic. Investigation is underway to determine the magnitudes of bulk and surface contributions to forward bias leakage. Surface accumulation of electrons may play a role in both parasitic sidewall conduction and increased p-type ohmic contact resistance.

Session T: Semiconductor Processing: Oxidation, Passivation

Thursday PM
June 21, 2007

Room: 129
Location: DeBartolo Hall

Session Chairs: Thomas Kuech, University of Wisconsin; Maria Losurdo, Institute of Inorganic Methodologies and Plasmas, IMIP-CNR

1:30 PM

T1, Late News

1:50 PM

T2, Pulse Thermal Processing of Nanomaterials: *Ron Ott*¹; ¹Oak Ridge National Laboratory

Oak Ridge National Laboratory (ORNL) in the past two years has utilized a high density plasma arc lamp technology and a process called pulse thermal processing (PTP) to process a multitude of materials associated with the electronics industries: such as photovoltaics, thin-film transistors, thin-film batteries, LED's, and magnetic media. The unique high density plasma arc lamp rapid thermal processing (RTP) capability at ORNL allows controlled manipulation of materials on the atomistic scale. This unique large area (currently up to $\sim 1,000 \text{cm}^2$) RTP capability is able to apply controlled heat fluxes (up to $20,000 \text{W/cm}^2$) to material surfaces with heating and cooling rates on the order of 10^4 to 10^5C/sec on the millisecond time frame. Because of the large area processing capability, a one-dimensional thermal field is established unlike the three-dimensional thermal field associated with lasers. These capabilities allow rapid controlled annealing which permits a unique opportunity to "freeze" specific microstructures, which permits direct evaluation of nucleation and growth events as a function of time and temperature. The unique nature of this tool allows the establishment of a direct correlation between microstructure and material performance. Pulse thermal processing (PTP) utilizing the high density plasma arc processing equipment, employs a preheat schedule in order to bring the material system up to a specific temperature, hold for a predetermined time, followed by pulsing several times (on the millisecond time scale) to much higher temperatures. This method is capable of processing large areas as well as decreasing total processing time to fraction of a second to seconds rather than minutes, which is typical of today's state-of-the-art rapid thermal processing. Due to the time and temperature limitations of previous rapid thermal processing methods, materials historically could not be processed on flexible substrates. It has been shown that PTP is able to process thin-film materials at elevated temperatures on flexible substrates, including polymers, with little-to-no thermal effects to the substrate. Pulse thermal processing is a very unique processing technology allowing the manipulation of materials on the nanometer scale and in many cases is an enabling processing tool for electronic applications. Because of the rapid heating rates, short processing time, and large area coverage PTP is able to form nanoscaled structures in materials at the device level, truly leading to state-of-the-art nanomanufacturing. PTP is a disruptive type technology, revolutionizing how thin-film and nanoparticle based electronic devices are processed, while maintaining the functionality of the materials at the nanoscale.

2:10 PM Student

T3, Low-Temperature PECVD OLED Encapsulation: *Dalong Zhao*¹; Min-Hao Lu²; Anna Chwang²; Mike Hack²; Thomas Jackson¹; ¹Pennsylvania State University; ²Universal Display Corporation

Organic light emitting diodes (OLEDs) have been used to fabricate attractive and efficient displays. Thin film encapsulants are of interest as an alternative to glass-to-glass encapsulation to protect OLED from degradation due to exposure to water or oxygen, and a range of barrier and encapsulation approaches are being pursued, including multi-layer barrier films¹ and deposited encapsulants.² We have encapsulated OLEDs with silicon nitride (SiN_x) deposited at low temperature ($<70^\circ\text{C}$) using plasma enhanced chemical vapor deposition (PECVD) from silane and atomic nitrogen. The deposition system (Ionic Systems) uses atomizer chambers and relatively

high-density RF plasma to atomize nitrogen gas before it enters the process chamber. The process chamber uses a lower density RF plasma to react the atomic nitrogen with silane and allows good quality silicon nitride deposition at temperatures less than 70°C. The low deposition temperature allows deposition on OLED structures without device damage. The system also uses a load lock to reduce moisture loading and contamination of the process chamber. The atomic nitrogen process also allows film stress to be controlled by varying film stoichiometry. Increasing silicon incorporation tends to make film stress more compressive and reducing silicon incorporation tends to make film stress more tensile. In this work, a minimum film stress of 2.9×10^8 dynes/cm², compressive, was obtained for a N₂/SiH₄ flow ratio of 9 (135/15). Our low temperature SiNx OLED encapsulation results are comparable to glass-to-glass encapsulation results for room temperature aging, and also show no observable delamination for accelerated testing at high temperature and humidity (60°C and 85% RH). We have also operated low-temperature silicon nitride encapsulated OLEDs for more than 12 hours in a hot water bath (55°C) with minimal degradation. Low temperature SiNx encapsulated OLEDs do show some dark spots that grow with operation, especially at high temperature, and we are working to reduce or eliminate these defects.

¹A. B. Chwang, M. A. Rothman, S. Y. Mao, R. H. Hewitt, M. S. Weaver, J. A. Silvermail, K. Rajan, M. Hack, J. J. Brown, X. Chu, L. Moro, T. Krajewski, and N. Rutherford, "Thin film encapsulated flexible OLED displays," *Appl. Phys. Lett.*, vol. 83, pp. 413–415, 2003. ²J. Lewis and M. Weaver, "Thin-Film Permeation-Barrier Technology for Flexible Organic Light-Emitting Devices," *IEEE J Sel Top Quant.*, vol. 10, Jan/Feb 2004.

2:30 PM Student

T4, Passivation of Surface States for Intersubband Quantum Box (IQB) Laser Structures: *Manish Rath¹*; Anish Khandekar¹; Gene Tsvid²; J. Shin²; Dapeng Xu²; Mithun D'Souza²; Dan Botez²; Thomas Kuech¹; ¹University of Wisconsin-Madison, Chemical and Biological Engineering; ²University of Wisconsin-Madison, Electrical and Computer Engineering

Semiconductor lasers whose active region is composed of a 2-D array of intersubband quantum boxes (IQBs) hold the promise to be significantly more efficient and reliable than many-stage (~30) quantum cascade (QC) lasers. Two most common proposed IQB structures are based on the AlGaInAs-InP and InGaAsP-GaAs material systems. IQB structures mainly consist of active boxes composed of an electron injector, a deep quantum-well (QW) active region and a Bragg reflector, and surrounded by current-blocking material (CBM). The fabrication of the structures requires e-beam patterning and transfer to an Si₃N₄ mask, reactive-ion etching and subsequent in-situ etch and regrowth. Metal-organic vapor phase epitaxy (MOVPE) is used as a primary growth technique. Efficient 4.7 μm emission from GaAs-based deep-QW intersubband devices has been reported previously. The sidewall-surface non-uniformity along the in-plane directions (x-y) of the active boxes, due to in-situ etch process, is not important since the intersubband-lasing transition energy is determined primarily by the active-well thickness (the z direction). However, at the nanoscale, the exposed sidewall surfaces along the z-direction as well as the in-plane directions pose a problem of Fermi-level pinning because of surface states which leads to complete carrier depletion across the active boxes. To minimize the formation of surface states and passivate the exposed surfaces, we have carried out in-situ etch and regrowth experiments with an annealing step, under arsine environment, on (110)-oriented GaAs substrates, which basically correspond to the IQB sidewall. Initially, a thick n-type GaAs layer was grown with a doping of 2×10^{17} /cm³ on top of a n-type (110)-oriented wafer. Subsequently, it was exposed to electron cyclotron (ECR) etch with chlorine/argon environment, which is used to create nanoposts during the IQB-structures fabrication. Then, in-situ etch with HCl and subsequent regrowth of n-type GaAs with doping level of 1×10^{17} /cm³ on this sample was carried out in a MOVPE reactor with and without arsine anneal. The use of a point-of-use purification on the HCl line was found to be essential to the reproducibility of the process. The annealing step was carried out before etch-regrowth with arsine partial pressure of 10⁻² Torr. Growth conditions will be presented in detail. Capacitance Voltage (CV) measurements were performed on the samples to verify the doping profile and to determine the existence of trapped charges due to surface states at the interface of GaAs grown before and after in-situ etch-regrowth. The results show that the purified HCl-based etch combined with an arsine anneal eliminate the charge trapping states at the interface and thus lead to the

removal of Fermi-level pinning for the IQB-device fabrication. This result will be verified on a GaAs quantum-well structure grown on a (100) GaAs substrate and presented in detail.

2:50 PM

T5, Fabrication of Nanometer-Scale Single Photon Detectors in InGaAsP/InP Heterostructures: *Minjun Yan¹*; Tim Hossain¹; Niu Jin¹; Shuang Zhang¹; Illesanmi Adesida¹; Omer Memis²; Alex Katsnelson²; Soon-Cheol Kong²; Hooman Mohseni²; ¹University of Illinois at Urbana-Champaign; ²Northwestern University

Photon detectors fabricated using InGaAsP/InP heterostructures have wide applications in medical imaging and military applications. Through the mechanisms of carrier focalization and augmentation, detectors fabricated with nanometer-scale dimensions have the potential of achieving sensitivities at single photon levels.¹ Preliminary theoretical work has shown that with an optimally designed heterostructure, and under an electric field, a hole produced by a single photon gets collected, and in return increases the local field, which injects many electrons to realize significant augmentation. Such a single photon detector has many advantages including low dark current in comparison with existing avalanche photodiodes. In this paper, we demonstrate the fabrication of single photon detectors in an InP/InGaAs heterostructure with dimensions down to 100 nm in diameter. We compare various masking techniques in order to realize high aspect ratio and high anisotropy in the fabricated structures. Our work utilizes patterning by electron beam lithography with PMMA resist and reactive ion etching (RIE) in methane-hydrogen mixtures. The fabrication process included planarization with polyimide, etch-back, and metallizations. Various analytical measurements using atomic force microscopy and scanning electron microscopy were utilized in assuring the integrity of these processes. We utilized three etch mask configurations to obtain anisotropic single photon InP/InGaAs detector pillars. The masks were NiCr, SiO₂/NiCr, and Ti/Pt/Au/NiCr. The last mask was studied to see whether the ohmic metallization and the NiCr metal mask could be integrated in a single step. The gas mixture CH₄/H₂ was chosen for etching due to its slow etch rate in order to accurately control the etch depth. Devices with dimensions ranging from 2 μm down to less than 100 nm were fabricated. The best aspect ratio was obtained using the SiO₂/NiCr. The origin of submicron bowling-pin-like InGaAsP/InP pillars for the etch mask of Ti/Pt/Au/NiCr was investigated. With the size of PMMA opening hole shrinking during metal evaporation, the deposited metal Ti/Pt/Au/NiCr had a trapezoid-shape where the edges and base eroded during etching thereby creating "bowling pin" effects especially for the 100 nm geometries. We will discuss the various features observed during the etching including micro-grass features for the mask of SiO₂/NiCr, which is due to the residual SiO₂ that could be removed by an additional Freon cleaning process. The polymer accumulation around the pillars during CH₄/H₂ etching resulted in a slight decrease in pillar dimensions however it promoted anisotropic vertical shapes. Results on electrical performances of the devices will be presented.

¹H. Mohseni et al., "A Novel Avalanche-free Single Photon Detector," *IEEE Processing of Indium Phosphide and Related Materials Symposium*, 2006, pp. 163-165.

3:10 PM Break

3:30 PM Student

T6, Electrical Characterization of Surface Passivants for InAs/GaSb Strain Layer Superlattice (SLS) MWIR Detectors: *Subhrangshu Mallick¹*; Siddhartha Ghosh¹; Jean Rodriguez²; Sanjay Krishna²; ¹University of Illinois at Chicago; ²University of New Mexico

In the last two decades InAs/GaSb SLS has emerged as a potential material for Mid-wavelength and Long-wavelength infrared (MWIR:3-5 μm and LWIR:8-14 μm) material. Its optical property has been reported to be comparable to the commonly used matured Hg_{1-x}Cd_xTe technology¹ and the detector fabricated from this SLS system shows comparable performance as that HgCdTe detectors for longer wavelength (MWIR and LWIR) applications. Especially at long wavelength applications (>10 μm) the growth of HgCdTe becomes extremely difficult because of an exact composition requirement. But because of comparatively easy growth InAs-GaSb SLS has the edge for longer wavelength application.¹ Surface passivation is a critical issue in narrow bandgap materials used for infrared application. A little amount of surface perturbation can bend the band at the surface,

resulting in an accumulation, depletion or inversion, hence changing the device characteristics. In InAs/GaSb SLS surface passivation is still an issue that is needed to be addressed thoroughly to push the performance of the devices beyond the currently reported results. In our work PECVD (2500C) deposited SiO₂, magneto-sputtered Si₃N₄ (room temperature), electron beam evaporated ZnS (room temperature) are selected as the potential materials for passivants. These passivants are compared on the basis of their insulation properties, Capacitance-Voltage (C-V) characteristics, and 1/f flicker noise characteristics. MIS structures were fabricated using these passivants and InAs/GaSb SLS. Insulation property of the passivants is considered to avoid any dielectric breakdown of the passivation layer, when the device underneath the passivant is subjected to a larger positive or negative bias (e.g. in avalanche photodiode). Voltage sweep across the MIS structure at 78K shows the PECVD deposited SiO₂ has the maximum dynamic resistance*area of more than 10⁸Ohm in between ±20V followed by ZnS and Si₃N₄ (Fig.1). Comparative C-V characteristic at 78K at 400 kHz shows SiO₂ MIS structure has the minimum hysteresis compared to ZnS or Si₃N₄ MIS structure (Fig.2). Similarly a lower 1/f noise power and hence a lower knee-frequency is also measured for SiO₂ passivated bulk InAs/GaSb SLS sample followed by ZnS and Si₃N₄ for 0V at 78K (Fig.3). A detailed analysis of the surface preparation along with the effect of different surface preparations on these performance characteristics for these passivants will be presented and discussed. A temperature and frequency variation on the C-V characteristics and a temperature variation of the 1/f noise measurement will also be presented to understand the interface properties of the passivant-SLS for a better device performance. This work is funded by the DARPA HOT MWIR Program and ARL Advanced Sensors CTA. ¹C. H. Grein, P. M. Young, M. E. Flatté, and H. Ehrenreich, J. Appl. Phys.78, 7143 (1995). ²G.J.Sullivan et al. J. Vac. Sci. Technol. B, 23,1 (2005).

3:50 PM Student

T7, Wet Thermal Oxides of Non-Lattice-Matched InAlP on GaAs: *Jing Zhang*¹; Thomas Kosel¹; Patrick Fay¹; Douglas Hall¹; Wayne Lewis²; Bob Yanka²; Thomas Rogers²; Walter Wohlmuth²; ¹University of Notre Dame; ²RFMD

The wet thermal oxides of MOCVD grown In_{0.485}Al_{0.515}P (lattice matched to GaAs) have been shown to exhibit excellent electrical properties,¹ and GaAs-based MOSFETs using these oxides as the gate dielectric have exhibited promising microwave performance, including an f_t of 17 GHz and an f_{max} of 74.8 GHz.² In this work, we report the first studies on the wet thermal oxides of MBE-grown, non-lattice-matched tensile-strained In_xAl_{1-x}P (x=0.45, 0.404 and 0.291) including electrical properties and microstructure. Current-voltage (I-V) measurements on MOS capacitors show low leakage current densities, and inversion is observed. Using MOS capacitor test structures on n-type GaAs, the electrical properties of 15 nm non-lattice-matched InAlP layers oxidized at 440°C in an H₂O/N₂ ambient are evaluated. Upon oxidation, expansion by 1.67X to 25 nm is observed by variable-angle spectroscopic ellipsometry. The oxidation rates are found to be 6.3 Å/min, 7.9 Å/min, and 12.1 Å/min for x = 0.45, 0.404 and 0.291, respectively. Five sets of typical I-V data are collected for capacitors fabricated using each InAlP mole fraction. The contact area for the test capacitors is 30 μm × 30 μm. The average leakage current densities at 1 V bias are J_L=1.36 × 10⁻⁸ A/cm², 7.8 × 10⁻⁹ A/cm², and 7.3 × 10⁻⁹ A/cm² for x = 0.45, 0.404 and 0.291, respectively, comparing favorably with the 3.8 × 10⁻³ A/cm² value achieved for similar MOS capacitors³ with an 11 nm thick oxide of lattice-matched In_{0.485}Al_{0.515}P. At higher bias voltages, the differences between the films are even more pronounced; J_L at 3 V decreases by a factor of four as the In mole fraction decreases from x = 0.45 to 0.291, suggesting that a higher bandgap InAlP oxide can be achieved with a non-lattice matched alloy containing less In and more Al. High frequency and quasi-static capacitance-voltage (C-V) measurements of MOS capacitor test structures exhibit accumulation, depletion and inversion for all of the InAlP oxide compositions, demonstrating that a clean oxide-semiconductor interface has been achieved. Transmission electron micrographs also show a clean and smooth interface between the oxide film and the substrate. From the quasi-static C-V characteristics, the relative permittivity of the In_xAl_{1-x}P oxides is determined to be 5.93, 5.84, and 5.14 for x = 0.45, 0.404 and 0.291, respectively. Based on the above electrical and microstructural studies, wet thermal oxides of non-lattice matched InAlP appear promising for use as the gate insulator in GaAs based MOSFETs. ¹Y. Cao, J. Zhang, et al., Appl. Phys. Lett. 86, 062105 (2005). ²Y.

Cao, et al., Proc. IEEE Compound Semiconductor Integrated Circuit Symp., p. 43 (2006). ³Y. Cao, et al., IEEE Electron Device Lett. 27, 317 (2006).

4:10 PM

T8, Improvement in the Insulating Properties of Native Oxides of InAlP: Michael Graham¹; Simona Moisa²; Xiaohua Wu¹; Dolf Landheer¹; Anthony SpringThorpe¹; Pedro Barrios¹; Sebastian Kleber²; Patrick Schmuki²; ¹National Research Council of Canada; ²University of Erlangen-Nuremberg

Producing chemically and electrically stable surfaces on III-V semiconductors is crucial for a number of important device applications. Passivation layers can be produced by deposition of silicon nitride or oxide or created by a variety of oxidation processes including thermal oxidation. Thermal oxidation data for AlGaAs and InAlAs in GaAs- and InP-based heterostructure devices have been reported, e.g.,¹⁻³ and the Al-containing oxides have often been found to possess good insulating characteristics. Recently, Al-containing thermal oxides on InAlP have been shown to be even more promising.⁴⁻⁶ This paper presents data on the thermal oxidation at 500°C in moist nitrogen (95°C) of MBE-grown InAlP layers (In_{0.525}Al_{0.475}P and In_{0.494}Al_{0.506}P) and of anodic oxides of In_{0.494}Al_{0.506}P lattice matched to GaAs. The oxides (20 nm–300 nm thick) have been characterized by Auger electron spectroscopy (AES), X-ray photoelectron spectroscopy (XPS), Rutherford backscattering spectroscopy (RBS), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). Oxides are amorphous and appear to be a mixture of indium phosphates and aluminum oxide. The oxidation kinetics are parabolic. Electrical measurements performed on metal-insulator-semiconductor (MIS) structures indicate that the oxides have good electrical properties. A brief oxidation in oxygen at 500°C following oxidation in moist nitrogen oxidizes residual indium particles present at the oxide/substrate interface and leads to improved electrical properties. The current density at a field of 1 MV/cm (8.6 V gate potential) is 1.7×10⁻¹⁰ A/cm², approximately two orders of magnitude lower after the final treatment in dry oxygen. The breakdown voltage is increased to 44 V, corresponding to a breakdown field of 5.1 MV/cm. Thus the films should be useful as insulators in some device applications. ¹F. A. Kish, S. J. Caracci, N. Holonyak, Jr., K. C. Hsieh, J. E. Baker, S. A. Maranowski, A. R. Sugg, J. M. Dallesasse, R. M. Fletcher, C.P. Huo, T. D. Osentowski and M. G. Crawford, J. Electron. Mat. 21, 1133 (1992). ²U. K. Mishra, P. Parikh, P. Chavarkar, J. Yen, J. Champlain, B. Thibeault, H. Reese, S. S. Shi, E. Hu, L. Zhu and J. Speck, IEDM'97, 21.1.1. ³R. Hussey, R. Driad, G. Sproule, S. Moisa, J. Fraser, Z. Wasilewski, J. McCaffrey, D. Landheer and M. Graham, J. Electrochem. Soc., 149, G581 (2002). ⁴A.L. Holmes, Ph. D. Dissertation, The U. of Texas at Austin, December 1999. ⁵P. Barrios, D. C. Hall, G. Snider, T. Kosel, U. Chowdhury and R. Dupuis, in SOTAPOCS XXXIV, 199th Meeting of The Electrochemical Society (Washington, DC, March 25-30, 2001). ⁶P. Barrios, D. C. Hall, U. Chowdhury, R. Dupuis, J. B. Jasinski, Z. Liliental-Weber, T. Kosel and G. Snider, Abstract, 43rd Electronic Materials Conference, Notre Dame, Indiana, June 27-29, 2001.

4:30 PM

T9, Complete Removal of Fermi Level Pinning at High-k Dielectric/GaAs (001) and (111)B Interfaces by a Silicon Interface Control Layer: *Masamichi Akazawa*¹; Hideki Hasegawa¹; ¹Hokkaido University

After many years, strong interests have recently come back to III-V MIS transistors as device candidates beyond the ultimate Si MOS scaling limit. Examples include InAlSb/InSb MIS HFETs¹, GaAs MOS transistors using Ga₂O₃/Gd₂O₃ etc, and MISFETs on vertical III-V nanowires by VLS growth. In such nanodevices, however, surface state problems become very serious, and success depends strongly on surface passivation. Passivation of nanodevices should be compatible with high-k MIS gate stack formation for effective gate control. Additionally, it should be applicable, not only to (001) surfaces, but also to non-(001) surfaces, since advanced III-V nanostructures include various non-(001) facets. We proposed and have been investigating the use of an MBE-grown Si interface control layer (Si ICL)² for passivation of III-V surfaces. However, the work has been limited to (001) surfaces in combination with Si-based non-high-k dielectrics. In this paper, we demonstrate that our Si ICL-based passivation structure can be combined with *ex-situ* deposition of high-k dielectric and that Fermi level pinning was completely removed from high-k dielectric/GaAs (001) and (111)B interfaces. Here, a structure of HfO₂/SiN_x/Si ICL/GaAs was investigated. Before HfO₂ deposition, a SiN_x/

Si ICL/GaAs structure was prepared by *in-situ* processing in a UHV multi-chamber system with *in-situ* XPS monitoring. First, n-type GaAs was grown by MBE. Then, after control of surface reconstruction of GaAs, a 1nm-thick Si ICL was grown by MBE at 300°C. Subsequently, a part of the Si ICL was converted to SiN_x by nitrogen radical beam in the same chamber. According to XPS study, the surface Fermi level was strongly pinned at 600-800 meV above VBM before Si growth in spite of clear surface reconstruction patterns. After Si ICL growth, large shifts of Fermi level of 250-420 meV took place toward CBM on all the surfaces except (001)-(2x4) surface. Particularly, large reduction of band bending was seen on Ga-stabilized (001) and (111)B surfaces. XPS data indicated that As acted as a surfactant during epitaxial growth of Si ICL. The resultant GaAs surface coated by a SiN/Si ultrathin double layer was found to be extremely stable to air-exposure even without a thick passivation dielectric. This is because the ultrathin oxynitride/Si ICL structure after air-exposure prevents subcutaneous oxidation remarkably well. This allowed *ex-situ* deposition of HfO₂ in a separate chamber by electron-beam evaporation in an oxygen atmosphere of 10⁻⁴ Torr. Subsequently, the sample was annealed at 400°C. MIS gate stacks having Al field plates were fabricated and characterized by capacitance-voltage measurements. The obtained data indicated a completely pinning-free swing of the surface Fermi level with bias voltage. The minimum value of interface state density was 6x10¹⁰ cm⁻²eV⁻¹. ¹R. Chau et al, IEEE Trans. Nanotechnol. 4, p.153 (2005). ²H. Hasegawa, Thin Solid Films 367, p.58 (2000).

4:50 PM

T10, Late News

Session U: Indium Nitride

Thursday PM
June 21, 2007

Room: 102
Location: DeBartolo Hall

Session Chairs: William Schaff, Cornell University; Steven Durbin, University of Canterbury

1:30 PM Student

U1, Conduction Band Offset and Schottky Barrier Formation at the InN/GaN Heterojunction: *Kejia (Albert) Wang*¹; Chuanxin Lian¹; Ning Su¹; John Timler²; Debdeep Jena¹; ¹University of Notre Dame; ²System Creations

In past few years, InN has attracted enormous interest due to its narrow band gap (~0.65 eV), small electron effective mass, high mobility, and high saturation velocity. Due to its unique properties, InN and its alloys with GaN and AlN are being actively considered for multijunction photovoltaic devices that span the whole solar spectrum. In a multijunction solar cell, the band offsets are crucial for charge transport and limit the efficiency of the devices. However, there few experimental studies of the band offset of InN with GaN (C.-F. Shih et al. Jpn. J. Appl. Phys. 44, 7892 (2005)). The theoretical conduction band offset between GaN and InN has been calculated to be 2.3 eV (C. G. Van de Walle and J. Neugebauer, Nature 423, 626 (2003)). In this work, we present an experimental measurement of this quantity through combined temperature-dependent vertical transport measurements, and capacitance-voltage measurements. An unintentionally doped InN layer was grown by RF-plasma molecular beam epitaxy on an n-type GaN substrate under optimized growth conditions reported earlier (Kejia Wang et. al, Appl. Phys. Lett. 89, 162110, 2006). From Hall measurement, the InN was found to be heavily n-type doped with electron mobilities ~ 1200 cm²/Vs. The n+ InN/ n GaN diode was fabricated by mesa etching and metal deposition. Temperature-dependent current-voltage (I-V) measurements were performed. The diodes showed rectifying behavior, indicating the formation of a Schottky barrier between InN and GaN. From the temperature dependent I-V measurement, a Schottky barrier height of 0.35 eV was determined. Capacitance-voltage (C-V) measurements of the same diodes results showed a slightly smaller Schottky barrier height of 0.25 eV. By solving Poisson's and Schrodinger's equations self consistently for

the InN/GaN heterojunction, and considering the polarization charge of InN and GaN, the band diagram of n-InN/nGaN heterojunction was plotted and quantitative agreement with the experimental Schottky barrier height was found. At the InN/GaN interface, a very heavy electron accumulation layer forms due to the combined effects of a large band offset, and a large electric field due to the polarization discontinuity. The conduction band maximum at the interface is about ~1.7 eV below the Fermi level, and the Schottky barrier height is about 0.48 eV if the image-charge induced barrier lowering is neglected. By considering the image force effect, the effective barrier height of the Schottky diode was about 0.36 eV, which is in good agreement with the experimental data. The experimentally extracted band offset is found to be 2.2 eV, in close agreement with theoretical predictions. The formation of a Schottky barrier is not surprising, considering the fact that the Fermi level in InN is inside the conduction band, and it has metallic transport in addition to a high electron affinity.

1:50 PM Student

U2, Effect of MBE Growth Conditions on Multiple Electron Transport in InN: *Tamara Fehlberg*¹; Gilberto Umama-Membreno¹; Brett Nener¹; Giacinta Parish¹; Chad Gallinat²; Gregor Koblmuller²; James Speck²; ¹University of Western Australia; ²University of California, Santa Barbara

High quality heteroepitaxy of indium nitride (InN), such as through molecular beam epitaxy, has only recently been realised. Fine tuning growth parameters such as buffer layers, flux ratio and substrate temperature remains an important focus. Much recent work has been conducted to correlate the crystal quality of InN films with growth conditions, but only simple single carrier transport characterisation is generally reported in such growth parameter studies. Accurate transport characterisation of InN is made difficult by the presence of multiple electron species in the material. At minimum each sample of InN has a bulk electron species due to unintentional n-type doping, and a surface electron accumulation due to Fermi level pinning at the c-plane/air interface. High levels of defects can further contribute to the presence of reduced mobility electrons in the material. Transport parameters calculated from single magnetic field Hall-effect measurements represent only an averaged contribution of all carrier species in the material. In this work a quantitative mobility spectrum analysis (QMSA) of multiple magnetic field (0-12 T) Hall-effect data was used to determine the individual transport properties of all electron species in InN films grown by plasma-assisted molecular beam epitaxy (PAMBE). 1 μ m thick In-polar InN layers were grown on optimised GaN buffer layers on semi-insulating (Fe-doped) Ga-polar GaN templates. The three samples studied were grown under different conditions; substrate temperature 440°C/In-droplet growth regime, 470°C/In-droplet regime and 450°C/N-rich (dry) regime. Significant difference exists for each film between the transport characteristics extracted for the multiple electron species and those calculated using only a single magnetic field, with the N-rich regime sample having average electron mobilities in the bulk over twice that suggested from single field calculations. While all films has similar bulk electron densities, at around 4 × 10¹⁷ cm⁻³, the In-droplet growth regime samples had superior mobilities (2150 cm²/Vs - 440°C and 2430 cm²/Vs - 470°C) to the N-rich growth regime sample (1730 cm²/Vs). The low mobility sheet carrier concentration is similar for both In-droplet regime samples and correlates with reported surface sheet carrier concentrations extracted using various measurement techniques. However, the low mobility sheet carrier concentration is much higher in the N-rich regime sample, and the low mobility electron peaks in the mobility spectrum are very broad. Since the surface morphology of the N-rich regime film is poorer than those grown under In-droplet conditions, it is likely that the broadness of the peak is related to the surface morphology. A larger spread in mobility for low mobility carriers is also seen in the In-droplet regime film grown at the higher temperature.

2:10 PM

U3, Controlling Carrier Type and Concentration in InN through Doping and Substrate Choice: *Craig Swartz*¹; Steven Durbin¹; Philip Anderson¹; Roger Reeves¹; Thomas Myers²; Sandeep Chandril²; Scott Ahrenkiel³; ¹University of Canterbury; ²West Virginia University; ³South Dakota School of Mines and Technology

InN has generated considerable interest in the last few years due to controversy over its bandgap. Although the precise value may still remain

a topic of discussion, significant efforts are now being made to understand the origin of the observed background carrier concentration and surface electron accumulation in as-grown samples, and to obtain p-type material. Capacitance-voltage measurements have been proven effective in revealing p-type conductivity despite the masking effects of the surface accumulation layer, which essentially short-circuits conventional (single magnetic field) Hall effect measurements. An alternative is employ the variable magnetic field Hall effect, which is able to separate the individual contributions from multiple conducting pathways – for example, surface/interfacial electrons and holes in the bulk. In this report, we describe direct observation of p-type InN using variable magnetic field Hall effect measurements on samples doped in-situ with Mg or doped via substrate impurity when growing on (111) yttrium-stabilized zirconia (YSZ). InN layers were grown using the plasma-assisted molecular beam epitaxy technique. Mg doped In-polar films were grown on Ga-polar MOCVD GaN substrates, and Mg-doped N-polar films were grown on sapphire with a thin N-polar GaN buffer layer. Other In-polar films were grown on lattice-matched (111) YSZ substrates. Film polarity was verified by KOH etching. For the lowest Mg concentration sample, the intensity of the typical 0.67 eV photoluminescence (PL) feature was essentially the same as that of our unintentionally doped (n-type) films. At higher Mg concentration, a faint PL peak appeared at 0.56 eV, to our knowledge the lowest energy feature yet reported for InN PL. If this feature is in fact due to transitions to the Mg acceptor, it suggests an acceptor energy approximately 110 meV above the valence band. We observed p-type layers in samples doped in-situ with Mg, using both variable magnetic field Hall effect and electrolyte-based capacitance-voltage (C-V) measurements. Variable magnetic field Hall effect measurements were made using a commercial 12 Tesla superconducting magnet and confirmed by measurements up to 31 Tesla at the National High Magnetic Field Laboratory in Tallahassee, Florida. These were analyzed with Quantitative mobility spectrum analysis and multiple carrier fitting, which both suggested a light hole. Interestingly, samples grown without Mg doping but on YSZ also showed a p-type layer indicated by the presence of a light hole. Unlike the Mg-doped samples, the n-type conduction of the film itself is still detectable, indicating the p-type layer is not in the bulk of the film, but only near the interface. The n-type carrier concentration measured from a 500 nm thick film was $2 \times 10^{17} \text{ cm}^{-3}$, which would require a thickness of several microns if grown on commonly used, more poorly lattice matched sapphire substrates.

2:30 PM

U4, Remarkable Reduction of Electron Concentration of In-Rich $\text{In}_x\text{Ga}_{1-x}\text{N}$ ($x \sim 0.7$) by Mg Doping: Akihiko Kikuchi¹; Junpei Kamimura¹; Katsumi Kishino¹; ¹Sophia University

Since the bandgap energy of InN has been considered to be 1.0–0.6 eV, InN and In-rich InGaN have attracted much attention as a promising material for near infrared opto-electronic devices such as laser diodes and solar cells. But the material quality is still insufficient to realize devices and p-type conductivity control also is not achieved. Recently it was reported that p-type InN region exists in Mg-doped InN layers which showed n-type conductivity in Hall effect measurement^{1,2}. The masking mechanism of p-type conductivity was explained that an electron accumulation layer and a charge depletion layer were generated at the surface due to Fermi-level pinning in conduction band for InN and In-rich InGaN¹⁻³. In this study, a remarkable reduction of electron concentration in Mg doped In-rich $\text{In}_x\text{Ga}_{1-x}\text{N}$ ($x \sim 0.7$) to be $8 \times 10^{15} \text{ cm}^{-3}$ was achieved. This value is one of the lowest electron concentrations in InN and In-rich InGaN. InN and In-rich $\text{In}_x\text{Ga}_{1-x}\text{N}$ ($x \sim 0.7$) layers were grown by an RF-plasma assisted molecular beam epitaxy on (0001) Al_2O_3 substrates with a 500 nm-thick nitrogen polar GaN buffer layer. The carrier concentration and mobility were evaluated by the van der Pauw method at room temperature. The residual electron concentration and mobility of 1 μm -thick undoped InN and $\text{In}_{0.75}\text{Ga}_{0.25}\text{N}$ layer was $1 \times 10^{18} \text{ cm}^{-3}$ and 1570 cm^2/Vs , and $2.9 \times 10^{18} \text{ cm}^{-3}$ and 151 cm^2/Vs , respectively. The Mg doping for an InN layer with the Mg beam equivalent pressure (BEP) of $5 \times 10^{-7} \text{ Pa}$ brought about reduction of carrier density into $1.5 \times 10^{17} \text{ cm}^{-3}$ with a mobility of 1141 cm^2/Vs but conductivity was still n-type. The In-rich $\text{In}_x\text{Ga}_{1-x}\text{N}$ ($x \sim 0.7$) layers were grown at 470°C, under fixed BEP of In, Ga and nitrogen but with changing the Mg BEP from 5.0×10^{-7} to $5.0 \times 10^{-6} \text{ Pa}$. The layer was grown 1 hr with a growth rate of 0.9–1.5 $\mu\text{m}/\text{hr}$. All the Mg doped samples showed n-type conductivity but electron concentration was less than 7×10^{17}

cm^{-3} . The lowest electron concentration was $8 \times 10^{15} \text{ cm}^{-3}$ with a mobility of 36 cm^2/Vs for Mg BEP of $1.0 \times 10^{-6} \text{ Pa}$. It was confirmed also that Mg doping affect the surface morphology and In composition. The very low residual electron density of the In-rich InGaN layer may relate to smaller amount of surface electron accumulation compared to InN. This result suggested that p-type conductivity control is easier for In-rich InGaN compare to InN, but it is favorable for device fabrication because the double heterostructure light emitting devices should have a p-type In-rich InGaN cladding layer. ¹R.E.Jones et al. Phys. Rev. Lett, 96, 125505 (2006). ²P. A. Anderson et al, Appl. Phys. Lett. 89, 184104 (2006). ³T. D. Veal et al, Appl. Phys. Lett. 89, 202110 (2006).

2:50 PM

U5, Optical Hall-Effect in Hexagonal InN: Tino Hofmann¹; Vanya Darakchieva²; Bo Monemar²; H. Lu³; William Schaff³; Mathias Schubert¹; ¹University of Nebraska-Lincoln; ²Linköping University; ³Cornell University

While common agreement on the band-gap properties of InN is achieved, the doping and transport mechanisms in InN are still highly unclear.^{1,2,3} InN grown by molecular beam epitaxy or metal-organic vapor phase deposition techniques is intrinsically n-conductive and the lowest intrinsic electron concentration reported so far was achieved using molecular beam epitaxy (MBE) with approximately 10^{17} cm^{-3} .⁴ In addition to the intrinsic n-type conductivity which is likely caused by Hydrogen and Oxygen acting as shallow donors as well as negatively charged dislocations an electron accumulation layer is formed on InN thin films surfaces.^{4,5,6} This accumulation layer presents an immanent complication in the contact based electrical investigation of free charge carrier properties in InN. Here we report on a new, alternative approach to investigate the free charge carrier properties in InN. The precise measurement of the optical Hall-effect - optical birefringence caused by free charge carriers upon interaction with an external magnetic field - which allows the determination of carrier type, concentration, mass, and mobility including their anisotropy in stratified semiconductor layer structures independent of the conductivity of the individual layers. A set of (MBE) grown samples with InN eplayer thicknesses from 500 to 2000 nm was investigated. We observe that both the carrier concentration at the surface and in the bulk drop with increasing layer thickness according to the same power law in the investigated thickness range. The major source for this decrease in surface and bulk carrier concentration is the decrease of the density of negatively charged dislocations with increasing layer thickness.⁴ We furthermore find a distinctly anisotropic Γ -point electron effective mass in the bulk were the effective mass parallel to the *c*-axis is smaller than the effective mass perpendicular to the *c*-axis. For bulk carrier concentrations above $8 \times 10^{18} \text{ cm}^{-3}$ the anisotropy vanishes. ¹H. Lu *et al.*, Appl. Phys. Lett. 77, 2548 (2000). ²C.H. Swartz *et al.*, physica status solidi (c) 2, 2250 (2005). ³C. S. Gallinat *et al.*, Appl. Phys. Lett. 89, 032109 (2006). ⁴V. Cimalla *et al.* Appl. Phys. Lett. 89, 172109 (2006). ⁵D.C. Look *et al.* Appl. Phys. Lett. 80, 258 (2002). ⁶I. Mahboob *et al.* Phys. Rev. Lett. 92, 036804 (2004).

3:10 PM Break

3:30 PM

U6, Direct Write Patterning of InGaN during Molecular Beam Epitaxy and Its Solar Cell Application: Xiaodong Chen¹; William Schaff¹; Lester Eastman¹; ¹Cornell University

Recently direct-write technologies have been considered as promising and novel approaches to the fabrication of electronic devices. So far there has only few direct-write techniques applied in III-nitrides during molecular beam epitaxy (MBE). Using a 50 μm diameter 1.06 μm pulse laser beam that is directed to controlled locations by scanning mirrors, direct-write patterning of InGaN during MBE was successfully achieved. With *z*-axis control of focal plane, we are allowed to have in- and out-of-focus change in laser beam size and power hitting on the growing materials. The feature width can alter from 40 μm to 100 μm with different laser focal plane position. The line depth can also be controlled between 20 nm and 2000 nm depending on the focal plane position and writing times. The results suggest that in-focus writing can provide the smallest exposure size and highest exposure power. Moreover, the surface morphology changes were observed when varying exposure speed and number of passes per exposure. The InGaN material system offers a substantial potential to develop high efficiency solar cells

due to the bandgap of this material system covering the whole solar spectrum including the visible region. One of the main challenges for Indium-based nitride solar cells is surface electron accumulation. In our previous study, it has been shown that direct-write patterning can realize lateral InGaN composition variations. A new approach to modification of surface properties is proposed to raise gallium (Ga) content locally on solar cell sidewalls by direct-write composition patterning during growth, seen in Figure 1. A single p-i-n InGaN junction cell was grown by MBE with 1.5 μm n-type bottom layer, 350 nm intrinsic layer and 90 nm p-layer. The In mole fraction is aimed at 80%. The growing material was exposed to laser when i-layer growth onset. The writing pattern and real wafer are shown in Figure 2 and 3 respectively. High Ga mole fraction is only created in region where mesa edge is defined so the parasitic conduction will be minimized.

3:50 PM Student

U7, Cross-Sectional Cathodoluminescence Study for 1 ML-InN Wells/GaN Matrix MQW Structures Grown by rf-Plasma-Assisted MBE: E. S. Hwang¹; H. Saito²; S. B. Che³; X. Wang⁴; Y. Ishitani³; A. Yoshikawa³; ¹Graduate School of Electrical and Electronics Engineering, and InN-Project as a CREST-program of JST, Chiba University; ²Graduate School of Electrical and Electronics Engineering, Chiba University; ³Graduate School of Electrical and Electronics Engineering, VBL, and InN-Project as a CREST-program of JST, Chiba University; ⁴InN-Project as a CREST-program of JST, Chiba University

Recently, we have proposed and achieved the fabrication of novel structure InN/GaN MQWs consisting of 1 monolayer (1-ML)-thick InN wells embedded in the GaN matrix under In-polarity growth regime. In this structure, generation of defects arising from large lattice mismatch (~11 %) can be avoided in principle. We have confirmed that no lattice-mismatch dislocations are introduced at the hetero-interface and also that high quality and atomically flat 1-ML or fractional mono-layer (FML) InN wells are inserted in the MQW structures.¹ In this novel MQW structure, excitons and holes in GaN can be effectively localized at the InN well due to the effects of large confinement potential at the well and smaller electronegativity of In than Ga, resulting in much stronger oscillator strength of excitons. In this paper, in order to confirm these properties in the proposed novel InN/GaN MQWs, cross-sectional cathode-luminescence (CL) properties were studied at room temperature. As is known well, CL is a suitable method for investigating optical properties with very high spatial resolution. In particular, cross sectional CL study is a powerful method to investigate how the 1-ML-thick InN wells effectively work as active luminescence area. We used Gatan-Mono-CL3 CL system in this study. The InN/GaN MQW structure was grown under In- and/or Ga-polarity growth regime by rf-plasma-assisted-MBE at 650°C. MOCVD grown ~3 μm -thick Ga-polarity GaN/sapphire substrate was used as a template for fabricating this MQW structure. First, structural properties of the MQWs were studied by conventional characterization methods such as XTEM, STEM and XRD measurements/simulations, and it was confirmed that the InN well layer thickness was exactly about 1 ML for the sample in the present study and the structural quality of the MQWs are extraordinary high. Also confirmed that the thickness of GaN barriers and the period of MQWs were about 14 nm and 10, respectively. From the spatially resolved panchromatic and monochromatic CL images for the cleaved sample surface, it was first confirmed that luminescence intensity in the MQW region exhibited drastically bright CL emission peaking at 400 nm. The integrated emission intensity for MQWs region was more than 10 times stronger than that for MOCVD grown high quality GaN template. Detailed spot-by-spot monochromatic CL characterizations around the MQWs with high magnification level were performed along the growth direction. From these results it was confirmed for the first time that the excitons in GaN can be effectively localized at 1-ML-thick InN wells even at room temperature, leading to probable developments of room temperature operating excitonic devices and nitride-based visible light emitters approaching up to green and red. ¹A. Yoshikawa et al, APL vol.90, No.6 2007.

4:10 PM Student

U8, Infrared Cathodoluminescence Measurements of InN Films: Takano Akagi¹; Kenichi Kosaka¹; Satoshi Harui¹; Hiroyuki Naoi¹; Tsutomu Araki¹; Yasushi Nanishi¹; ¹Ritsumeikan University

InN is currently under extensive investigation as an important semiconductor

with many promising applications. As with many optoelectronic materials, the success has been limited by the control of both point defects and extended structural defects. Thus an important subject in InN technology is to ascertain the cause negatively affecting the optical characteristic. Cathodoluminescence (CL) imaging technique is widely used to study spatially resolved optical properties of semiconductor films. It was confirmed by using this technique that threading dislocations (TDs) act as non-radiative recombination centers in GaN. As for InN, however, such a correlation was not done. In this study, we performed infrared CL mapping of InN films. InN films used in this study were grown at ~550°C on nitridated (0001) sapphire substrates with a low-temperature-grown InN buffer layer by radio-frequency plasma-assisted molecular-beam epitaxy. The film thicknesses were approximately 500 nm. We selected two samples of largely different TD density: sample A with screw- and edge-TD densities of $6 \times 10^8 \text{ cm}^{-2}$ and $7 \sim 9 \times 10^9 \text{ cm}^{-2}$, respectively and sample B with those TD densities of $4 \times 10^9 \text{ cm}^{-2}$ and $2 \sim 4 \times 10^{10} \text{ cm}^{-2}$, respectively, as revealed by cross-sectional transmission electron microscopy measurements. CL measurements were performed at approximately 150 K with an electron-beam acceleration-voltage of 5 kV by using Hamamatsu Photonics G7754-01 (1.2 ~ 2.4 μm) liquid nitrogen cooled PIN photo diode as a detector. Sample A exhibited a single CL emission with a peak energy of 0.73 eV and a line width of 76 meV, whereas sample B showed a higher CL peak energy of 0.77 eV and a broader line width of 109 meV, confirming that sample A is superior in quality to sample B. Panchromatic CL images showed that the density of dark spots for sample A was approximately $5 \times 10^8 \text{ cm}^{-2}$ whereas that for sample B was approximately $1 \times 10^9 \text{ cm}^{-2}$. We also varied the electron penetration-depth nominally from 70 to 1400 nm by changing the electron-beam acceleration-voltage from 2 to 15 kV, but the positions of the CL dark spots did not change noticeably. These results indicate that the sample with higher density of TDs has higher density of CL dark spots and that the CL dark spots align almost vertically in the films. Thus we consider that the CL dark spots correspond to TDs and that dislocations act as non-radiative recombination centers in InN. This work was supported by the MEXT (Ministry of Education, Culture, Sports, Science, and Technology) through Grant-in-Aids for Scientific Research (A) #18206003 and for Scientific Research in Priority Areas "Optoelectronics Frontier by Nitride Semiconductor" #18069012, Academic Frontier Promotion Project, and the 21st Century COE Program.

4:30 PM

U9, Low Temperature Epitaxial Growth of Nonpolar InN on m-ZnO: Hiroshi Fujioka¹; Kazuya Mitamura¹; Atsushi Kobayashi¹; Kouhei Ueno¹; Jitsuo Ohta¹; Masaharu Oshima¹; Hidetaka Amanai²; Satoru Nagao²; Hideyoshi Horie²; ¹University of Tokyo; ²Mitsubishi Chemical Group Science and Technology Research Center

Growth of nitride semiconductors with nonpolar planes has attracted much attention because they are free from the undesirable effects of the built-in fields. The use of nonpolar ZnO substrates is a straightforward strategy to obtain high quality nonpolar nitride films because they have the same crystal structure as the nitrides (wurtzite) and the lattice mismatches are reasonably small. We have grown nonpolar InN films on m-ZnO using a low temperature PLD growth technique^{1,2} because reduction in growth temperature is inherently necessary to suppress the interface reactions and take advantage of ZnO substrates. Surfaces of m-ZnO with stepped and terraced structures were achieved by high temperature annealing in the air with the use of a box made of ceramic ZnO.² Then, the samples were transferred into a UHV-PLD with a background pressure of 5×10^{-10} Torr. An In metal target (99.9999% purity) was ablated by a KrF excimer laser ($\lambda = 248 \text{ nm}$, $\tau = 20 \text{ ns}$) with an energy density of 3.0 J/cm^2 and a repetition rate of 5 Hz. Nitrogen gas (99.9999% purity) was introduced into the PLD chamber through an RF plasma source operated at 320 W during the growth. The nitrogen pressure during the InN growth was 2.0×10^{-5} Torr. Firstly, we tried to grow InN on m-ZnO at 550°C but the crystalline quality of the film was quite poor due to the serious interfacial reactions between InN and ZnO. To solve this problem we reduced the growth temperature down to 300°C and found that high quality m-InN grows on m-ZnO. EBSD pole figure measurements revealed that the m-InN films do not contain any other phases or domains. FWHM values for X-ray rocking curves for 0002, 1-100, and 11-20 turned out to be 0.19°, 0.80°, and 0.24°, respectively. These results indicate that the combination of the nonpolar ZnO substrates and the PLD low temperature growth technique

is quite promising for achieving high quality nonpolar InN. References: ¹Y. Kawaguchi et al., Appl. Phys. Lett. 87, 221907 (2005). ²A. Kobayashi et al., Appl. Phys. Lett., 90, 041908 (2007).

4:50 PM

U10, Late News

Session V: Thermoelectric Materials

Thursday PM
June 21, 2007

Room: 155
Location: DeBartolo Hall

Session Chairs: G. Jeffrey Snyder, California Institute of Technology;
Timothy Sands, Purdue University

1:30 PM Invited

V1, Stable Nanostructured Thermoelectrics: *Mercouri Kanatzidis*¹; Timothy Hogan²; Ctirad Uher³; Duck Young Chung⁴; F. Poudeu¹; C.-I. Wu²; H.-J. Khong³; ¹Northwestern University; ²Michigan State University; ³University of Michigan; ⁴Argonne National Laboratory

There is a strong incentive to develop novel thermoelectric materials for power generation with a vastly improved thermoelectric performance. Nanomaterials have a role to play in meeting this challenge because of expectations for enhanced power factor and greatly reduced thermal conductivity in suitably chosen systems. Therefore general, convenient synthetic routes to bulk nanostructured materials, designed to be thermodynamically stable and thus practically permanent, are needed. First, one needs to address the issue: what is a nanomaterial when it comes to thermoelectric research? We will then present several such concepts in preparing bulk materials containing nanometer-sized coherent and non-coherent inclusions. Coherent nanometer sized inclusions in a semiconductor matrix such as PbTe can serve as sites for scattering of acoustic phonons to lower the thermal conductivity. This research is expected to teach us how to design and prepare bulk inexpensive nanostructured advanced thermoelectric materials. We also expect to extract fundamental scientific information regarding the influence of nanostructures on TE properties. The thermoelectric figure of merit is thereby predicted to improve because of the ability to decouple carrier scattering from phonon scattering mechanisms. Results to this effect involving AgPbSbTe_{2+m} (LAST-m) and NaPbSbTe_{2+m} (SALT-m) will be presented.

2:10 PM Student

V2, Effects of Fermi Level Pinning by Indium on Thermoelectric Properties of Pb_{(1-x)Sn_xTe} Alloys: *Vladimir Jovovic*¹; Suraj Jootu Thiagarajan¹; Joseph West¹; Joseph Heremans¹; Tanya Komissarova²; Dmitry Khokhlov²; Andrei Nicorici³; ¹Ohio State University; ²Moscow State University; ³Institute of Applied Physics, Moldova Academy of Sciences

Indium pins the Fermi level of Pb_{(1-x)Sn_xTe}^{1,2} alloys to an energy that depends on both x and the temperature. The Mahan-Sofa theory³ predicts that a local increase in density of states, through hybridization for instance, should increase the thermopower of the semiconductor at a given carrier density. This can lead to an increased thermoelectric power factor and figure of merit. In this work, we investigate if such can be the case in the Pb_{(1-x)Sn_xTe}:In system. To test this concept we synthesized and measured a series of single crystal alloys with Sn level ranging from x = 10 to 30 at.% doped with 0.01 to 10 at.% indium. We also explored the effect of adding 0.01 to 1 at.% Ge. We report galvanomagnetic and thermomagnetic data: the adiabatic transport properties are measured in a transverse magnetic field ranging from -1.9 to +1.9 Tesla and over a range of temperatures from 80 to 440K. Electrical conductivity, thermal conductivity, thermopower, Hall coefficient and adiabatic and isothermal transverse Nernst-Ettingshausen coefficient measurements are used to deduce the carrier density, effective density of state mass, carrier mobility and scattering coefficient. Our findings reveal that there is indeed an enhancement in thermopower, possibly due to the hybridization of In levels via the Mahan-Sofa theory. We also give the minimum In concentration required to pin Fermi energy, and the effects of excess In on the transport properties. We have attempted to find the optimal

Sn concentration which maximally enhances thermopower at temperatures above room temperature. ¹S. Takaoka, T. Itoga, K. Murase, Jpn. J. App. Phys. 23, (2) 1984. ²T. G. Abaidulina, S. A. Némov, V. I. Proshin, Yu. I. Ravich, Semiconductors 30, (12) 1996. ³G. D. Mahan and J. O. Sofo, Proc. Natl. Acad. Sci. USA 93 (7436) 1996.

2:30 PM

V3, Thermoelectric Properties of Nanostructured Bulk Composites in the PbTe-Sb₂Te₃ System: *T. Ikeda*¹; Eric Toberer¹; G. Snyder¹; Vilupanur Ravi¹; Sossina Haile¹; ¹California Institute of Technology

It has recently been recognized that composite structures with nanoscale features can result in dramatic improvements in the figure of merit of thermoelectric materials. This is largely due to enhanced phonon scattering, resulting in decreased thermal conductivity. The objective of this work is to achieve nanostructures in bulk form and to investigate the effect of nanostructures on thermoelectric properties. A system of two immiscible thermoelectric materials, PbTe and Sb₂Te₃, was examined. These compounds were selected because under the right synthesis conditions a metastable phase Pb₂Sb₆Te₁₁ appears and it is decomposed to nanosized lamellar structures composed of the two thermoelectric materials by heat treatments. Eutectic PbTe-Sb₂Te₃ alloys were synthesized by quenching from the liquid state. The microstructures of the as-quenched and the annealed alloys were examined. Then, the thermal conductivities and the electrical resistivities of these materials were measured as functions of inter-lamellar spacing.

2:50 PM

V4, Analysis of Thermoelectric Properties of Nanostructured SiGe: *Daryoosh Vashaee*¹; Hohyun Lee¹; Gang Chen¹; Ming Tang²; Mildred Dresselhaus³; Dezhi Wang⁴; Xiaowei Wang⁴; Zhifeng Ren⁴; Pawan Gogna⁵; Richard Blair⁵; Jean-Pierre Fleurial⁶; ¹Massachusetts Institute of Technology, Department of Mechanical Engineering; ²Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science; ³Massachusetts Institute of Technology, Department of Physics and Department of Electrical Engineering and Computer Science; ⁴Boston College, Department of Physics; ⁵California Institute of Technology, Jet Propulsion Laboratory

We present models analyzing recent experimental results on thermoelectric properties of nanostructured SiGe that have shown significantly improved figure-of-merit ZT. The increase in ZT is mainly due to the reduction in thermal conductivity. These structures have also shown an improvement in thermoelectric power factor. For a high ZT to happen, the size of nanoparticles must be comparable to the effective phonon mean free path to reduce the thermal conductivity, and much larger than the electron (or hole for p-type material) mean free path to preserve the electron mobility. The model takes into account the contributions from phonon, ionized impurity, and grain boundary (GB) scattering for electrons, and the phonon-phonon, point defect, electron phonon, and GB scattering for phonons. The interface boundaries are modeled by taking into account the space charge effect and additional scattering due to the rotation of the crystal orientation at GBs. The free rotation of the crystal orientation among the nano-particles can result in a potential barrier for electrons and strong mosaic scattering for phonons. It is shown that the intervalley scattering at GBs can increase the transmission probability and reduce the boundary resistance for electrons. The space charge barrier at GBs can decrease the electrical conductivity. However, this barrier also increases the Seebeck coefficient by filtering the hot electrons that go over the barrier. We will discuss the optimum doping concentration that can maintain or increase the effective power factor.

3:10 PM Break

3:30 PM Student

V5, Temperature Dependence of Enhanced Seebeck Coefficient in Ge-Rich Si-Ge Alloys: *Nathaniel Oster*¹; Joel Harringa²; Bruce Cook²; ¹Iowa State University, Department of Materials Science and Engineering; ²AMES Laboratory, Materials and Engineering Physics Program

Research in the 1950's and 1960's revealed the presence of an anomaly in the Seebeck coefficient of Ge-rich alloys near the 85 atomic percent composition. As the bandstructure changes from that of pure Ge to that of Si, the number of equivalent valleys in the conduction band reaches a maximum, which gives rise to increased intervalley scattering. A study of this effect was

performed as part of the larger issue of how bandgap engineering and the formation of in order to answer the larger question of how compositional engineering can be employed to design advanced thermoelectric materials possessing enhanced complexities in their bandstructure. Heretofore, this effect was only understood in terms of conduction band minima. We present results that suggest a similar phenomenon associated with the valence band in Si-Ge. A series of Ge-rich compositions above and below 85 atomic % Ge were prepared by melting, grinding, and hot pressing. The samples were nominally doped with boron to yield p-type conductivity. Composition was determined by x-ray diffraction through precision lattice parameter determination. Hall effect measurements showed that all samples possessed a positive Hall coefficient, indicating p-type conductivity, with a 300K carrier concentration ranging from a minimum of $7 \times 10^{16} \text{ cm}^{-3}$ to a maximum of $2 \times 10^{17} \text{ cm}^{-3}$. The temperature dependence of the Seebeck coefficient was measured from 300K to 873K. The potential for exploiting this enhancement in Seebeck coefficient for thermoelectric power conversion applications is discussed.

3:50 PM

V6, Thermoelectric Properties Full Heusler Alloys Based on Fe_2VAl : Donald Morelli¹; ¹Michigan State University

While the thermoelectric properties of the so-called half-Heusler alloys have been very well studied over the last ten years, those of the full Heusler alloys have been considered hardly at all. This is mostly because most Heusler alloys are metallic and are not good thermoelectrics. However, it has recently been shown that several full-Heusler alloys based on the Fe_2VAl composition exhibit semiconductor-like behavior and interesting thermoelectric properties. This behavior is thought to arise from a gap or pseudo-gap in the electronic density of states at the Fermi level induced by hybridization of the aluminum (s,p) and transition metal (d) orbitals.

We have just begun investigating a series of full Heusler alloys of the composition $\text{Fe}_2\text{VAl}_{1-x}\text{Si}_x$. The Si atoms are thought to substitute for Al and dope the material n-type. These alloys were fabricated by arc melting the constituents under flowing argon on a water-cooled copper crucible. X-ray diffraction analysis showed that alloys with $x = 0, 0.03, 0.06, 0.10,$ and 0.20 all display the expected cubic full-Heusler structure with no presence of peaks due to other phases. Whereas the nominally undoped $x = 0$ alloy is p-type with a temperature independent Hall coefficient, alloys with $x = 0.03$ and 0.06 show a crossover from p-type behavior at high temperature to n-type behavior at low temperature with the crossover point dependent on x . This crossover from p-type to n-type behavior in Hall coefficient is reflected in the Seebeck coefficient S . While the $x = 0$ sample shows a positive thermopower through the temperature range studied, the Si-doped samples all display negative S . The temperature at which the negative maximum in S occurs in the $x = 0.03$ and $x = 0.06$ samples correlates with the crossover temperature in the Hall coefficient. This behavior suggests that Fe_2VAl is a semimetal with both holes and electrons available for conduction, consistent with recent band structure calculations for these alloys. Upon substitution of Si for Al the Fermi level is moved up further into the conduction band and the electrons begin to dominate transport. By combining the Seebeck coefficient data with the electrical resistivity ρ of these alloys, we can determine the thermoelectric power factor, S^2/ρ . For the $x = 0.10$ sample the power factor exceeds that of state of the art bismuth telluride-based thermoelectric materials at room temperature. This is a very exciting result that highlights the promise of these alloys for potential thermoelectric energy conversion applications.

4:10 PM Student

V7, Lanthanum Telluride for High-Temperature TE Applications via Mechanical Alloying: Andrew May¹; Jean-Pierre Fleurial²; G. Jeffrey Snyder¹; ¹California Institute of Technology; ²Jet Propulsion Laboratory

Lanthanum telluride is a promising n-type conductor for high temperature thermoelectric applications, with a $ZT > 1$ at 1273 K. Mechanical alloying has been demonstrated as a room temperature synthesis technique for this refractory compound. Data describing pertinent thermoelectric properties will be presented for $\text{La}_{1-x}\text{Te}_4$ ($0 \leq x \leq 0.3$) between room temperature and 1000°C . When ($0 \leq x \leq 1/3$) the defect Th_3P_4 structure is present, which leads to a metal-insulator transition as the relative number of lanthanum vacancies (x) increases thereby removing electrons from the system. This transition makes

a fundamental model that accurately describes all compositions difficult to obtain. A semi-empirical model describing the Seebeck coefficient, electrical resistivity, carrier mobility and thermal conductivity for the full range of compositions will be presented.

4:30 PM

V8, Zintl Phases as Thermoelectric Materials: Franck Gascoin¹; ¹Université Montpellier 2

Because of their ability to convert waste heat into electricity, thermoelectric materials have attracted renewed interest for environmentally benign power generation. With significant improvements in efficiency, thermoelectric materials could provide a substantial amount of electrical power from automotive exhausts, geothermal vents, and other sources. Zintl phases are ideal candidates for efficient thermoelectric materials because they are typically small-bandgap semiconductors with complex structures. Thus, they can be placed between metals (low Seebeck coefficient, low resistivity) and insulators (high Seebeck, high resistivity). Furthermore, their complex structures can lead to low lattice thermal conductivity. Together, these characteristics make Zintl phases potential high figure of merit thermoelectric materials. Zintl phases can be described as polar intermetallic phases as they are made of elements whose electronegativity differs grandly. Thus, an electron transfer from the most electropositive element to the most electronegative occurs and is the consequence of the formation of two distinct sub-networks, anionic and cationic. While the two sub-networks are ionically connected, strong covalent bonds exist within the anionic network. This peculiarity that places the Zintl phases between the classical alloys and the ionic salts (they are sometimes called "metallic salts") allow the modification of one sub-network without disrupting the other one. Thus, such phases offer the possibility to finely adjust dopant concentration without disrupting electronic mobility, which is essential for optimizing thermoelectric material efficiency. The following compounds will exemplify this true potential: the Zintl solid solution $\text{Ca}_x\text{Yb}_{1-x}\text{Zn}_2\text{Sb}_2$ in which the carrier concentration varies with the value of x . The two isostructural compounds $\text{Yb}_{11}\text{Sb}_{10}$ and $\text{Ca}_{11}\text{Sb}_{10}$ that show very low lattice thermal conductivity due to their very complex 0-dimensional structure. $\text{Yb}_{14}\text{MnSb}_{11}$, a transition metal Zintl phase that is simply the best p-type materials for high temperature application as it supplants the traditional state of the art high temperature material SiGe by a factor of two!

4:50 PM

V9, Complex Zintl Phases for Thermoelectric Devices: G. Jeffrey Snyder¹; ¹Caltech

Complex Zintl phases and polar intermetallics make ideal candidates for thermoelectric materials because the necessary "electron-crystal, phonon-glass" properties can be engineered with an understanding of the Zintl chemistry. Zn_4Sb_3 achieves high thermoelectric figure of merit by having extraordinarily low lattice thermal conductivity that can be attributed to the presence of disorder interstitial zinc atoms and nanometer sized domains. A recent example is the discovery that $\text{Yb}_{14}\text{MnSb}_{11}$, a transition metal Zintl compound, has twice the zT as the SiGe based material currently in use at NASA. This talk will outline a strategy to discover new high zT materials in Zintl phases, and presents results pointing towards the success of this approach.

Session W: Spin-Dependent (or Spintronic) Electronic Materials

Thursday PM
June 21, 2007

Room: 131
Location: DeBartolo Hall

Session Chair: Xinyu Liu, University of Notre Dame

1:30 PM Student

W1, Correlation between Zeeman Splitting of Band Edges and Curie Temperature in $Ga_{1-x}Mn_xAs$: Raja Chakarvorty¹; Shaoping Shen¹; Xinyu Liu¹; Jacek Furdyna¹; Malgorzata Dobrowolska¹; Rafal Jakiela²; Adam Barcz²; ¹Department of Physics, University of Notre Dame; ²Institute of Physics, Polish Academy of Sciences

The recent research interest in the field of spin-based electronics has generated a demand for materials that combine magnetism with large magneto-optical response. In that context III-Mn-V diluted magnetic semiconductors have emerged as promising materials for devices where spin of the carriers can be used to manipulate and store information. The most extensively studied semiconductor in this family is $Ga_{1-x}Mn_xAs$. It is important to emphasize that success of any device involving a high degree of spin polarization will depend not only on achieving an above-room-temperature Curie temperature (T_c), but in equal measure on the presence of a large Zeeman splitting of the carriers. In this connection primary emphasis so far was given to experimental efforts aimed at raising the Curie temperature and understanding the nature of ferromagnetism in this material. At the same time much less effort has been devoted to understand the effect of magnetism on the band structure and particularly on the details regarding the s , p - d exchange.¹⁻⁵ In this work we performed systematic magnetic circular dichroism (MCD) measurements on $Ga_{1-x}Mn_xAs$ samples grown by MBE on semi-insulating GaAs substrates. We kept Mn concentration on a similar level (~1%) in all our samples but by controlling the substrate temperature, and/or Be co-doping we varied the compensation level and therefore carrier concentration. We observed that the Zeeman splitting of band edges correlates directly with Curie temperature of the samples, namely samples with high T_c display large Zeeman splitting. In addition we also observed that the Zeeman splitting of the band edges correlates with the hole concentration rather than with Mn concentration. Our results show that the exchange interaction between the Mn spins and the band carriers is mediated by the hole localized at the Mn acceptor. This observation indicates that the nature of p - d exchange interaction is different than in II-Mn-VI diluted magnetic semiconductors. This observation opens an important question about the nature of the s , p - d exchange interaction in GaMnAs and the understanding of this issue may be crucial to our understanding of III-V ferromagnetic semiconductors. ¹J. Szczytko et al., Phys. Rev. B 59, 12935 (1999). ²B. Beschoten et al., Phys. Rev. Lett. 83, 3073 (1999). ³J. Szczytko et al., Phys. Rev. B 64, 075306 (2001). ⁴K. Ando et al., J. Appl. Phys. 83, 6548 (1998). ⁵T. Hartmann et al., J. of Superconductivity 16, 423 (2003).

1:50 PM Student

W2, Terahertz to Vacuum UV Generalized Magneto-optic Ellipsometry on Chlorine-Doped ZnMnSe: Giant Kerr Effect, Band-to-Band Transitions and Charge Transport Parameters: Mario Saenger¹; Lars Hartmann²; Heidemarie Schmidt²; Michael Hetterich³; Tino Hofmann¹; Mathias Schubert¹; ¹University of Nebraska-Lincoln; ²University of Leipzig; ³University of Karlsruhe

Dilute magnetic semiconductors may combine semiconducting and ferromagnetic properties, and may become essential building blocks for spintronic devices. Among the investigated dilute magnetic semiconductors the ternary alloy ZnMnSe previously revealed attractive potentials for spin aligner or transport materials. Despite many efforts, much is still unknown about the peculiarities of diluted semiconductors. Magneto-optic investigations provide very useful insights into spin-dependent electronic band structure, absorption, dielectric and magnetic polarizabilities, and charge transport properties. Spectroscopic magneto-optic studies of ZnMnSe have not been

exhaustive.⁽¹⁾⁽²⁾ Here we employ for the first time magneto-optic generalized ellipsometry over the wide spectral range from the Terahertz region to the vacuum ultra violet. A set of molecular beam epitaxy grown $Zn_{1-x}Mn_xSe$ samples in the composition range from $x = 0$ to 0.28 is explored. Optical Hall effect measurements in the Terahertz and Farinfrared range shed light on charge transport properties as a function of the magnetic field.⁽³⁾ Special emphasis is placed on the below-band-gap and above-band-gap spectral regions from 0.75 to 5eV, where measurements are done in a quasi-Kerr configuration. We observe strong magnetic-field induced chiral birefringence, which results in giant polarization rotation and ellipticity in the vicinity of the exciton-mediated band-to-band transition energy as a function of the magnetic field. The room temperature magneto-optic birefringence identifies the Zeeman splitting energies of the Γ -point valence and conduction band transitions by virtue of a dielectric function tensor model expanded from our previous work⁽⁴⁾, and developed here for magnetic field induced chiral anisotropy. Research supported by NSF in MRSEC QSPIN at University of Nebraska-Lincoln, and by the German Federal Ministry of Education and Research within the Young Scientist Competition in Nanotechnology. ¹Y.X. Zheng, et al., J. Appl. Phys. 81, 5154 (1997). ²T. Yasuhira, et al., J. Phys.: Condens. Matter 10 (1998) 11611. ³T. Hofmann et al., Appl. Phys. Lett. 88 (2006) 043105. ⁴J. Kvietkova et al., Phys. Rev. B 70 (2004) 045316.

2:10 PM Student

W3, Photoinduced Spin Dynamics in Ferromagnetic GaMnAs: Jingbo Qi¹; Ying Xu¹; Norman Tolk¹; Xinyu Liu²; Jacek Furdyna²; Illias Perakis³; ¹Vanderbilt University; ²University of Notre Dame; ³University of Crete

We report the temperature dependence of photoinduced spin dynamics in ferromagnetic $Ga_{0.95}Mn_{0.05}As$ ($T_c \sim 90K$) by time resolved polar Kerr rotation. The investigated ferromagnetic GaMnAs sample was 300nm thick and was grown by LT-MBE. Pump-probe measurements were performed using a laser with ~150-fs-wide pulses and a repetition rate of 76 MHz. The pump light had an average power of 10 mW, equivalent to a pulse energy of 0.13 nJ. The pump and probe beams had an energy ratio 10:1. The measured photoinduced temporal Kerr rotation signal can be decomposed into three exponential decay terms characterized by the decay constants t_1 , t_2 , and t_3 , respectively. Temperature dependent studies of these components show that 1) the t_1 has a magnitude of the order of ~0.4ps, which mainly reflects a contribution from the optical coherent response; 2) The component t_2 with a time scale up to ~40ps and the component t_3 increasing from ~180ps to ~790ps as the temperature decreases are found to be related to the photoexcited hole spins and electron spins, respectively. Ultrafast pump-probe measurements of magnetization showed coherent oscillations associated with the precession of Mn spins at temperatures below about 40K (~ $T_c/2$). We attribute the precession to the local laser heating effect and the resultant change of the magnetic anisotropies. At temperatures between ~ $T_c/2$ and T_c , the minor variance in the uniaxial anisotropy (K_{1u}) and the cubic anisotropy (K_{1c}) still keeps the ratio K_{1u}/K_{1c} larger than 1, and hence the in-plane easy axis and spontaneous magnetization is still along the uniaxial [110] direction. No oscillatory behavior can be observed. Whereas at temperatures below ~ $T_c/2$ the direction of in-plane magnetic easy axes depends on the interplay between K_{1u} and K_{1c} , and are determined by $\phi(t) = \arccos(K_{1u}(T(t))/K_{1c}(T(t)))/2$. The magnetization precesses around the time-dependent easy axis resulting in the oscillatory behavior observed in the temporal Kerr rotation signal. Based on our measurements of the oscillatory behavior in the polar Kerr rotation signal, we can provide a complete new description of relaxation of the overall photoinduced magnetization for GaMnAs under compressive strain. At temperatures below ~ $T_c/2$, the photoinduced magnetization rotation includes both contributions from free carrier spins and local Mn moments. When the temperature is between ~ $T_c/2$ and T_c , relaxation of the net magnetization is mainly associated with the photogenerated carrier spins. At high temperatures ($>T_c$), demagnetization dynamics is ascribed to spin relaxation of the photoexcited carriers.

2:30 PM Student

W4, Spin Wave Resonances and Surface Spin Pinning in (Ga,Mn)As Films: YingYuan Zhou¹; Yong-Jin Cho¹; Zhiguo Ge¹; Shaoping Shen¹; Xinyu Liu¹; Malgorzata Dobrowolska¹; Jacek Furdyna¹; ¹University of Notre Dame

We report a study of exchange-dominated nonpropagating surface and bulk spin-wave modes in (Ga,Mn)As films grown by molecular beam

epitaxy, with emphasis on the angular dependence of these modes and the corresponding surface spin pinning conditions. We have observed multi-mode spin wave spectra in (Ga,Mn)As films with thicknesses between 100 to 250 nm using the ferromagnetic resonance technique. The direction of the magnetic field H applied in these measurements was varied within the plane of the layer, as well as out of the layer plane. The field corresponding to the main (strongest) resonance peak at each orientation was used to calculate the four bulk magnetic anisotropy parameters (K_{2n} , K_{2l} , K_{4n} , and K_{4l}) and the g -factor of the magnetic films. The dependence of the spin wave modes on the orientation of H was analyzed in terms of two fundamental models: the surface inhomogeneity (SI) model,¹ and the volume inhomogeneity (VI)² model. Typically, when H is normal or near normal to the sample plane (i.e., $H||[001]$), a spectrum consisting of a series of well-resolved SW modes was observed. However, as H is rotated significantly away from the normal, at some orientation a “critical angle” was found, at which only the single uniform mode was observed. As H was rotated further and approaches the in-plane direction (such as the $[110]$ direction), a multiple-mode spectrum re-emerged, which we ascribed in part to the appearance of a surface spin excitation due to unpinned surface spins. Using a simple SI model, which takes account of a dynamic surface spin pinning as well as surface anisotropy,^{1,3,4} we were able to explain qualitatively most of the features of the spin wave resonance spectra observed in our (Ga,Mn)As films. In addition, the analysis of the observed spin wave resonances in terms of surface spin pinning allowed us to determine the values of the exchange stiffness constant D and of surface anisotropy in (Ga,Mn)As films studied in this work. Furthermore, the effects of temperature, low temperature annealing, and chemical etching on the surface spin wave resonance have also been investigated in an attempt to identify the localization of the surface mode. These data suggest that the surface anisotropy (i.e., surface spin pinning) exists at both the film/substrate interface and at the film surface, indicating that the surface anisotropy arises primarily from the abrupt step in Mn ion or in carrier (hole) concentration at the two boundaries of the (Ga,Mn)As film. ¹H. Puzkarski, Prog. Surf. Sci., 9, 191 (1979). ²A. M. Portis, Appl. Phys. Lett., 2, 69 (1963). ³P. E. Wigen, Thin Solid Films 114, 135 (1984). ⁴A. Maksymowicz, Phys. Rev. B 33, 6045 (1986).

2:50 PM

W5, Electrically Controlled Non-Volatile Spin-Based Memory Devices: Yury Semenov¹; Hani Enaya¹; Ki Wook Kim¹; John Zavada²; ¹North Carolina State University; ²U.S. Army Research Office

The feasibility of a new type of non-volatile spin-based memory device is examined theoretically. The specific device structure consists of a ferromagnetic (FM) dielectric layer, a semiconductor quantum dot (QD), and a hole reservoir separated from the QD by a permeable barrier. A non-magnetic quantum well (QW) filled with itinerant holes e.g. through modulation doping, can be used as the desired reservoir. The QD can be embedded either inside or outside the FM layer so long as there is a common interface. The operating principle of the proposed device concept is based on the exchange interaction between the itinerant holes in the QD and the magnetic ions in the non-metallic FM layer. First, the hole spins are aligned (although unpolarized) along the QW/QD growth axis due to the specific property of the holes in planar semiconductor structures. The magnetization in the FM layer is chosen to be oriented along the in-plane direction. The QD is prepared initially in a depopulated state through proper bandgap engineering with the neighboring reservoir and the permeable barrier. This corresponds to the state “0”. Once the holes are injected into the QD by an applied gate bias, the hole wave function extending into the FM layer lead to an exchange interaction with the magnetic ions. The resulting deviation of the FM magnetization from the layer plane produces a self-consistent potential that reduces the total free energy and forms a second stable state. The resulting polaron formation corresponds to state “1” which remains stable even after the bias is turned off, i.e., non-volatility is achieved. When a reverse bias pulse is applied, the holes are drained out of the QD back into the reservoir, thus erasing the spin memory. This device concept was analyzed in terms of free energy calculation that involves the contribution of holes populating the QD, their interaction with the FM layer, and the magnetic energy of the FM layer. The reservoir controls the QD chemical potential establishing the equation for hole population. The calculation results illustrate the following advantages of the proposed non-volatile device compared to the conventional CMOS-based memory: (i) excellent scalability, potentially down to a level

of a few holes by reducing the size of the QD (10-15 nm); (ii) extremely low erase/write (E/W) switching energy (intrinsic energy loss on the order of 0.1 aJ); (iii) high speed E/W operation that is limited primarily by the rate of magnetization rotation (<1 ns); (iv) easy electrical read-out based on the capacitance difference between the populated and depleted states. Furthermore, a high integration density is possible since only two terminals, the substrate and gate electrodes, are used for the device operation.

3:10 PM Break

3:30 PM Student

W6, Magnetic Anisotropy of Heavily Mn Doped (Ga,Mn)As Epilayers: Yong Jin Choi¹; YingYuan Zhou¹; Shaoping Shen¹; Xinyu Liu¹; Jacek Furdyna¹; ¹University of Notre Dame

Based on the mean-field Zener model,¹ the Curie temperature (TC) of (Ga,Mn)As is determined by the hole and Mn concentrations in the GaAs matrix. One way of increasing the value of TC of (Ga,Mn)As is therefore to increase its Mn content. Previous reports suggests, however, that self-compensation from Mn interstitials (whose concentration increases with increasing Mn content) saturates the hole concentration, and thus limits the TC of (Ga,Mn)As.² Moreover, introducing very high Mn concentrations (above 10%) also leads to the formation of MnAs precipitates. Recently, two methods have been attempted to overcome these bottlenecks. Method (1) is to decrease the growth temperature of (Ga,Mn)As to as low as 150-190°C, which results in the growth of (Ga,Mn)As films with high Mn content without precipitation of MnAs clusters as long as the film thickness is small (ca. 10 nm).³ Method (2) is to co-dope (Ga,Mn)As with Si, a n-type dopant for GaAs, which allows the maximum Mn concentration to exceed 10% in thin (Ga,Mn)As films.⁴ We have used both these methods to fabricate (Ga,Mn)As with a Mn concentration of over 10%, with the aim of determining how such increase in the Mn content affects magnetic anisotropy. During the growth, in situ RHEED has shown good 2D growth in both procedures for films up to several tens of nm without detectable MnAs precipitation. We have then systematically studied the magnetic anisotropies in these heavily Mn-doped (Ga,Mn)As thin films by SQUID, ferromagnetic resonance, and magnetotransport measurements. At this point our characterization of ultrathin (~10 nm) (Ga,Mn)As films with ~10% Mn grown by using Method (1) is significantly more advanced. Specifically, magnetization measurements show that the as-grown sample fabricated by this method exhibited a TC around 140 K; and clear ferromagnetic resonance peaks and anomalous Hall effect are observed up to TC for this samples. Interestingly, in this sample we do not observe any significant change in TC after low-temperature post-growth annealing, but it should be mentioned that the saturation magnetization decreases and magnetic anisotropy is significantly altered by such thermal treatment. Currently systemic analysis regarding the magnetic anisotropy in these heavily doped (Ga,Mn)As films are underway. In this regard, the possible roles of Mn concentration and Si co-doping will be investigated, and with an eye on understanding their effects on the concentration of Mn interstitials. ¹T. Dietl et al., Science 287, 1019 (2000). ²K. M. Yu et al., Phys. Rev. B 68, 041308(R) 2003. ³S. Ohya et al., cond-mat/0612055. ⁴T. Tanikawa et al., IEEE Transactions on Magnetics (submitted).

3:50 PM Student

W7, Magnetotransport Properties of GaMnAs Ferromagnetic Semiconductor Tri-Layer Structure Grown on ZnMnSe Buffer: S. J. Chung¹; D. Y. Shin¹; Sanghoon Lee¹; X. Liu²; J. Furdyna²; ¹Korea University; ²University of Notre Dame

The magnetotransport properties have been investigated in GaMnAs/GaAlAs/GaMnAs ferromagnetic semiconductor tri-layer structure grown on the ZnMnSe buffer layer. The introduction of ZnMnSe buffer layer is a key idea that realizes spin-valve like structure, which provides opportunity to investigate the spin scattering effect using Hall measurement. Since the buffer layer of Zn_{1-y}Mn_ySe with $y=0.2$ has larger lattice parameter than that of Ga_{1-x}Mn_xAs with $x=0.03$, the ferromagnetic GaMnAs layer is under strong tensile strain. This strain condition results in perpendicular anisotropy for trilayer ferromagnetic system, which allows us to study magnetization behavior by Hall measurement. Furthermore, the magnetic properties, such as Curie temperature (TC) and coersivity, of bottom GaMnAs layer differs from those of top GaMnAs layer due to the proximity effect between ferromagnetic GaMnAs and paramagnetic ZnMnSe buffer layer. Four possible magnetic

configurations (parallel or anti-parallel) in ferromagnetic tri-layer system are realized during the magnetic field scan due to different coersivity of two GaMnAs layers. The Superconducting Quantum Interference Devices (SQUID) measurement reveals that the easy axis of ferromagnetic tri-layer system is in perpendicular direction as expected from tensile strain. Temperature dependence of remanent magnetization(M_r) shows that T_c of top and bottom layers are about 45K and 55K, respectively. Hysteresis loops obtained below 45K show two-step behaviour which indicates different coercive fields for two GaMnAs layers in the structure. The same two step hysteresis loops as observed in SQUID measurement are obtained in Hall resistance (HR) data taken with current in-plane (CIP) configuration. The magnetoresistance (MR) data measured simultaneously with Hall resistance shows indication of tunneling magnetoresistance (TMR) effect due to the spin scattering between two layers. Though the structure shows only 0.04% of TMR ratio due to the experimental configuration (i.e., CIP configuration), this study clearly demonstrates spin scattering effect in ferromagnetic semiconductor tri-layer structure.

4:10 PM Student

W8, Investigation of the Anomalous Hall Effect for (Ga,Mn)As with Different Hole and Mn Concentrations: Zhiguo Ge¹; Shaoping Shen¹; Xinyu Liu¹; Jacek Furdyna²; Malgorzata Dobrowolska³; ¹University of Notre Dame

We present a systematic study on the anomalous Hall effect (AHE) in (Ga,Mn)As layers measured as a function of hole and Mn concentrations. AHE in (Ga,Mn)As layers has already been investigated extensively by numerous researchers. It is commonly accepted that AHE in (Ga,Mn)As could be described by two mechanisms: the side-jump mechanism or skew-scattering. These two mechanisms can be expressed mathematically by $R_{\text{hall}} \sim R_{\text{xx}}^n M$, where R_{hall} is the AHE resistance, R_{xx} is the longitudinal resistance, M is the magnetization, and the power n is a scaling parameter that equals 1 if the side-jump mechanism is dominant, and 2 if the AHE is dominated by skew scattering. However, the experimental results obtained so far are insufficient to establish clearly which of the two mechanisms is dominant, or to give a clear picture of the dependence of n on the properties of the sample, such as the hole and the Mn concentrations. In this study we have investigated two groups of samples, grown by low temperature molecular beam epitaxy (MBE). One group consists of four samples with Mn concentration x ranging from 0.02 to 0.08, x being determined by the growth temperature. The second group consists of four specimens with a much lower Mn concentration, $x = 0.01$, and have been co-doped with Be, as a means of adjusting the hole concentration h . Note that the quoted values of x refer to our estimate of substitutional rather than total Mn concentration. Magnetization data were obtained by magneto-optical Kerr effect (MOKE) at various temperatures using magnetic field up to 5T. At each temperature we also carried out transport measurements from which the AHE data and longitudinal resistance were obtained simultaneously. The magnetization data were fitted using the scaling theory and selecting the value of n for optimal fits. We found that for the samples of the first group, the AHE can be described very well by the two mechanisms mentioned above, or the combination of both. Specifically, the value of n is found to vary with x : for the $x = 0.04$ sample, $n \approx 2$, and for the $x = 0.06$ sample, n is found to lie between 1 and 2, indicating both the side-jump mechanism and skew scattering may coexist in that range of x . For the second (Be-co-doped) group, the scaling theory also gives excellent fits. However, the value of n found in this case is far below 1.0. This indicates that when the Mn concentration is low, the AHE in the (Ga,Mn)As is governed by other processes than either the side-jump mechanism or skew-scattering. We plan to conduct measurements under higher magnetic field, up to 14T, to further study the behavior of AHE in these specimens.

4:30 PM

W9, Novel Ferromagnetic Mn-Doped ZnGeAs₂ Chalcopyrite with Curie Point Equal to 367 K: Liudmila Koroleva¹; Sergey Marenkin²; Sergey Varnavskii³; Vitalii Pavlov¹; Denis Zashcherinski¹; Ritta Szymczak⁴; Witold Dobrowolski⁴; Kilansky Lukaz²; ¹M.V. Lomonosov Moscow State University; ²Kurnakov Institute of General and Inorganic Chemistry RAS; ³Kurnakov Institute of Inorganic and General Chemistry RAS; ⁴Institute of Physics PAS; ⁵Polish Academy of Science

In this work a new ZnGeAs₂:Mn chalcopyrite is described in which

Curie point is reached 367 K. This is highest Curie point in A^{II}B^{IV}C^V2:Mn spintronics systems. The samples of Zn_(1-x)Mn_xGeAs₂ (0 <= x <= 0.18) were obtained by melting of stoichiometric proportion of ZnAs₂ and Ge high purity powders. Manganese was doped according hypothetical cutaway ZnGeAs₂ - MnGeAs₂. X-ray powder diffraction was shown that all samples doped Mn were identified as ZnGeAs₂ and had single phase. Composition of X-ray diffraction patterns was shown that the volume of unit cell decreased as the Mn content increase, that is shown Mn-to-Zn supernatant solution. Components content was controlled with use of fluorescence analysis. Study of composition components along the sample length is showed that balance Zn:Ge:As = 1:1:2. Along the sample Mn-allocation was regularly in the limits of a measurement error. Magnetization M , electrical resistivity, magnetoresistance and Hall effect of this system were studied. The temperature dependence of magnetization has a complicated character. For example at the temperature diminution in sample with $x = 0.18$ the sharp decrease of magnetization at temperature $T_s \sim 86$ K is observed in magnetic field $H = 0.6$ kOe. This decrease become less sharp in higher fields and at $H = 11$ kOe disappears. The T_s -value is twice as large as that at $H = 9$ kOe. At $T_k < T_s$ the sharp increasing of M with the T-growth is observed. Difference between FC and ZFC magnetization take place at $T < T_k$. Shift of the hysteresis loop of FC sample was observed at $T = 5$ K. Similar behavior of M took place in other compounds of this system. The above-listed magnetic properties at $T < T_s$ are characteristic for spin glasses. By this means the ferromagnetic - spin glass transition occurs in T_s that is reentrant spin glass behavior. This is cluster spin glass since $M(T)$ dependence at $T < T_k$ obeys of Langevin function. All samples had a hole type of conductivity with carrier concentration $p \sim 10^{19}$ cm⁻³. Resistivity temperature dependence was typical for nondegenerative semiconductor. Magnetoresistance is smaller than 4 % at $H = 8$ kOe. The origin of the ferromagnetism in diluted magnetic semiconductors has been investigated using the first principles electronic structure calculation in work Sato, Akai, Mahadevan et al. In these systems the effective exchange interaction are mainly determined by competition the double-exchange and the superexchange interaction. Chalcopyrite semiconductors are stabilized by intrinsic defects that form stable complexes with Mn. Obviously that in Zn_(1-x)Mn_xGeAs₂ spin glass state presents at low temperatures in which the conductivity is lower than at high temperature and superexchange prevails; on the contrary the double-exchange prevails at high temperature.

4:50 PM

W10, Late News

Session X: Graphene and Carbon Nanotubes

Thursday PM
June 21, 2007

Room: 138
Location: DeBartolo Hall

Session Chairs: Mark Miller, University of Utah; Glenn Solomon, National Institute of Standards and Technology

1:30 PM

X1, Strong Field Effect in Epitaxial Graphene on a SiC Substrate: Gong Gu¹; Shu Nie²; Randall Feenstra²; Yue Ke³; Robert Devaty³; W. Choyke³; Michael Kane¹; Siun-Chuon Mau¹; ¹Sarnoff Corporation; ²Carnegie Mellon University; ³University of Pittsburgh

We report the first observation of strong field effect in epitaxial, as opposed to exfoliated, graphene thin film at room temperature. The graphene was formed by graphitizing the Si face of a 4H-SiC substrate at $\sim 1300^\circ\text{C}$ in ultrahigh vacuum. The n^+ doped ($10^{18}/\text{cm}^3$) substrate has a pre-grown, 2-micron thick, p -type ($7 \times 10^{14}/\text{cm}^3$) epi layer atop the Si face. The graphene was estimated to be 2 to 3 monolayers thick by in situ Auger spectroscopy. Gold source/drain contacts were deposited through a shadow mask. The graphene was then patterned into islands by conventional photolithography and oxygen plasma etching. Here, the n^+ substrate serves as the gate electrode, and the p epi layer, depleted at applied gate voltages in testing, as the gate dielectric.

The channel length is 0.35 mm, and the width is 1.5 mm. The drain-to-source channel conductance was measured by sweeping drain current versus drain-to-source voltage from 0 to 0.1 V, at gate-to-source voltages from 2 to 10 V. The linear curve, confirmed by additional drain voltage sweeps from 0 to 1 V, indicating good contact injection. Although the pn junction formed by the n+ substrate and the p-type epi was reverse biased, significant gate leakage was measured. Employing a small signal, distributed circuit model, as well as the measured gate leakage data, the channel conductance versus gate bias characteristics were derived. Minimum channel conductance consistently occurs at ~5 V gate biases, followed by increased conductance with increasing gate voltage. The electron field effect mobility extracted from the average slope of the curve is 235 cm²/Vs, and that from the maximum slope at high gate voltages is 310 cm²/Vs. Some measurements exhibit increasing channel conductance with decreasing gate voltage <5 V, but it is not clear if this can be attributed to the field effect of holes. Measurements of the hole field effect are prevented by the device structure where the pn junction would be forward biased with negative gate voltages. In order to confirm that the channel conductance dependence on gate bias is indeed an effect in graphene, we measured the conductance between two gold contacts without graphene in between, and found no gate voltage dependence in the shunt conductance. Compared to earlier work, the successful observation of strong field effect in epitaxial graphene is attributed to graphene active layer patterning as well as the device structure eliminating un-modulated portion of the channel. The mobility is lower than that of the exfoliated graphene, possibly because of scattering from step edges (which form a disordered arrangement according to atomic force microscopy) on the 8° miscut substrate. This simple device, without possible complication from a dielectric deposited onto graphene, show the feasibility of epitaxial graphene based transistors.

1:50 PM Student

X2, Morphology and Electronic States of Graphene on SiC (0001) Surfaces: *Shu Nie*¹; Randy Feenstra¹; ¹Carnegie Mellon University

The morphology and electronic states of graphene on SiC(0001) surfaces are studied using scanning tunneling microscopy and spectroscopy (STM/S), low-energy electron diffraction (LEED), Auger electron spectroscopy (AES), and atomic force microscopy (AFM). The graphene is formed by vacuum annealing of the SiC at about 1300°C, with most work performed on the Si-face. Prior to the graphitization the SiC is H-etched at 1600°C,¹ resulting in an ordered step-terrace structure with <1-100>-oriented steps due to unintentional miscut of the wafer. After graphitization the overall step structure as seen by AFM is preserved but the edges of the steps are rougher and small monolayer-deep holes appear on the surface. A much different morphology is found in preliminary studies of the C-face, with a multi-domain graphene arrangement on the surface. For the Si-face we observe 5x5 and 6x6 reconstructions based on STM and LEED,² with the latter dominating after sufficient annealing times or temperature. For a well formed 6√3x6√3 surface, AES indicates the presence of 3.2±0.5 monolayers of graphite on these surfaces. In STM filled-state images, the 5x5 surface appears as a hexagonal array of protrusions (each consisting of several individual topographic maxima) whereas the 6x6 appears more as a hexagonal array of depressions, consistent with prior work.^{2,3} Tunneling spectra acquired on both surfaces are similar, with peak energies relative to the Fermi level of -2, -0.5, +0.3 and +0.8 eV for the former and -2.1, -0.5, +0.5 and +1.0 eV for the latter. Spectra from both surfaces reveal non-zero conductance at Fermi level, indicating their weakly metallic nature. Spatially resolved spectroscopy has been performed on the 5x5 surface, revealing that filled states at -2.0 and -0.5 eV have their weight distributed centrally on the topographic protrusions, whereas the empty state at +0.3 eV is distributed uniformly over the surface and the state at +0.8 eV has a minimum in its density on the protrusions. Comparison of these results with theoretical expectations for the surface band structure will be discussed. In addition, STS has been performed over a wide range of tunnel current magnitudes, in an effort to detect any limitation in the transport through the graphene layer. For tunnel currents up to 10 nA, no such limitation is found, indicating relatively high mobility in the graphene layer. Further such studies of the transport in the graphene are in progress. ¹V. Ramachandran et al., J. Electron. Mater. 27, 308 (1998). ²P. Mårtensson, F. Owman, and L. I. Johansson, Phys. Stat. Sol. (b) 202, 501 (1997). ³W. Chen et al., Surf. Sci. 596, 176 (2005).

2:10 PM

X3, Fabrication and Characterization of Graphene Transistor Grown on 6H-SiC: *Kanji Yoh*¹; Tsubasa Ishizaki¹; Keita Konishi¹; Takashi Matsuda¹; Satoru Tanaka²; ¹Hokkaido University; ²Kyushu University

Recently, keen attention is directed to single layer carbon sheet (graphene) whose transport is described as relativistic Dirac fermion with zero effective mass.^{1,2} Room temperature mobility of 100,000cm²/Vs is reported for samples of graphene sheet printed from graphite chip. Unlike carbon nanotube, graphene devices have greater potential of integration because they can be selectively grown on SiC substrates.³ Here we report the fabrication and electrical characterization of graphene sheet grown on 6H-SiC substrate. The polished Si-face 6H-SiC wafer is initially H₂ etched at 1360°C, then monolayer graphene sheet is grown in vacuum by the decomposition of the surface followed by the synthesis of graphene sheet with substrate temperature of 1,500°C for 3 minutes. The monolayer formation can be verified by moiré pattern in-situ STM measurements.³ FET structure was defined by using conventional photolithography. Ti/Au layer was used as Ohmic contact and gate electrode. Silicon dioxide (200nm) was used as a gate oxide between the top gate electrode and graphene channel. Saturation of drain current behavior was observed at relatively low drain voltage. The current saturation at 180mV was observed in almost all measured devices. Current modulation by gate voltage was not observed. Drain current through graphene channel was observed to overlap with substrate current. Graphene layer and SiC substrate of various conduction type exhibited diode characteristics. Schottky barrier height of metals on Si-face SiC is known fit a linear line as a function of workfunction. Schottky barrier height for graphene was estimated to range from 0.38 to 0.62 eV. These values are much lower than the linear fit by 300mV in average with the corresponding workfunction. This result would suggest some atomic bonding between carbon atoms and underlying silicon atoms. The leakage current through Schottky barrier seems to be much lower than the observed drain current when source/drain is biased between 0 to 1V. So, the contribution from the leakage current through substrate by back-to-back Schottky diode is estimated to be negligibly small in most cases. The remarkable feature of the I-V characteristics is that the current kink ranged between V_{ds} ≅ 50m to 180mV. Beyond this bias voltage, drain current exhibit saturation characteristics. The Hall measurements revealed carrier concentration of 1x10¹⁵/cm² and mobility of 380cm²/Vs a room temperature, respectively. The ohmic contact resistance and the sheet resistance of the graphene were 250Ω and 10Ω, respectively. Although the transistor drain current was limited to 10nA range, the Hall sample showed current drivability of I_{max} = 460A/mm. We will also present our approaches to achieve semiconductor mode conduction in graphene. ¹K.S.Novoselov et al, Nature 438, pp.197-200 (2005). ²Y.Zhang et al, Nature 438, pp.201-204 (2005). ³K.Hayashi et al, Jpn.J.Appl.Phys.44, pp.L803-L805 (2005).

2:30 PM Invited

X4, Charge and Spin Coherent Transport Studies in Graphene: *Barbaros Oezylmaz*¹; Philip Kim¹; ¹Columbia University

Recently it has become possible to fabricate atomically thin sheets of graphite which are referred to as graphene. Graphene is a strictly 2D crystal and can be viewed as an unrolled single wall Carbon nanotube. Its unique band structure leads to remarkable electronic transport properties which are fundamentally different from that of two 2D systems realized in semiconducting heterostructures. Perhaps the most intriguing example is the unusual quantization of the Quantum Hall effect. Furthermore, graphene is likely to become an important material system in the fields of nanotechnology and spintronics. For example, its mean free path and both its phase and spin coherence length are expected to be very long. I will present experiments, which address the phase coherence length and spin coherence length in this novel 2 dimensional electron gas. I will start with the discussion of electronic transport in graphene ribbons patterned down to a width of ~ 20 nm. I will show that the finite size of such ribbons leads to the formation of a band-gap. Low temperature experiments show that the phase-coherence length in such samples is of the order of 1 μm. Such a long phase coherence length allows the direct observation of quantum interference phenomena in ring shaped graphene nanoribbons. I will continue with experiments addressing the spin coherence length in graphene. For these studies I have fabricated graphene based lateral spin valves. The spin injection has been achieved by means of ferromagnetic Co/Cu/Co multilayer electrodes. I will conclude my talk with

experiments in which we locally modulate the carrier density in graphene ribbons by means of a top gate. These studies allow us to explore the rich physics of graphene based pn-junctions.

3:10 PM Break

3:30 PM Student

X5, Determination Method of Energy Band Gap of Carbon Nanotube by High Temperature Dependence of Current: Masatoshi Maeda¹; Takafumi Kamimura²; Shin Iwasaki²; Kazuhiko Matsumoto³; ¹University of Tsukuba; ²Osaka University; ³Osaka University, Core Research for Evolutional Science and Technology-JST

We have established the new approach to measure the energy band gap (E_{gap}) of the carbon nanotube (CNT). CNT is the useful element for the future nano devices such as a CNT FET, biological sensors with high sensitivity, etc. For these applications, the determination of the E_{gap} of CNT is quite important as E_{gap} influences the device performances. An E_{gap} of semi-conducting nanotube is so far, mainly measured by a photo-luminescence (PL). In this measuring method, however it is necessary to set CNT isolated from the substrate. Therefore, PL technology cannot apply to the CNT devices for the measurement of the E_{gap} in which CNT directly contacts to the substrate. Another method to determine the E_{gap} is to measure a diameter of CNT by atomic force microscope (AFM). The diameter of CNT is directly related to the E_{gap} by the simple formation. In the present research, we have established new approach for the determination of the E_{gap} of individual CNT by measuring the temperature dependence of the CNT current from room temperature to 900°C. The sample was prepared as follows; Al_2O_3 was used as the substrate. The layered electrodes and catalyst were patterned on the substrate using the photo-lithography and lift-off process. The CNT was grown between two electrodes by thermal chemical vapor deposition. After the growth of CNT, the sample was then, set in an electric furnace and two electrodes were connected to the bias source. During the heat-up process of furnace from room temperature to 900°C, DC bias was applied between two electrodes and the CNT current was monitored. During the heat-up process, the CNT current starts to increase drastically around 700°C. The CNT current in logarithm scale is almost linearly proportional to the inverse of the temperature. This is owing to electrons directly excited by the thermal energy from the valence band to the conduction band. The E_{gap} was obtained from the slope of the CNT current, and it was found to be $E_{\text{gap}} = 0.9$ eV. After the measurement of CNT current at high temperature, the diameter of CNT was confirmed by AFM. The diameter of the CNT is $d = 0.92$ nm. Therefore, the energy band gap of CNT can be calculated from the CNT diameter using the simple relation, $E_{\text{gap}} = 2 \gamma_0 a_{\text{c-c}}/d$ [1], where γ_0 and $a_{\text{c-c}}$ are the constant, and found to be $E_{\text{gap}} = 0.88$ eV. The E_{gap} obtained from the temperature dependence of CNT current and from the diameter are well coincided. Therefore, it was confirmed that the E_{gap} of CNT can be determined from the temperature dependence of CNT current. ¹J. W. G. Wildoer, L. C. Venema, A. G. Rinzler, R. E. Smalley and C. Dekker, Nature 391, 59 (1998).

3:50 PM Student

X6, Silicon Supported Porous Anodic Alumina Templates with Long-Range Order for Vertical Nanoscale Devices: Joshua Smith¹; Aaron Franklin¹; Qingling Hang¹; Timothy Fisher¹; Timothy Sands¹; David Janes¹; ¹Purdue University

For over a decade, widespread research on nanowires and nanotubes has revealed the vast potential for incorporating these structures into nanoscale electronics. However, the ability to efficiently fabricate nanowire and nanotube-based devices on pre-functionalized substrates remains a challenge. The use of porous anodic alumina (PAA) to template the growth of these nanostructures has been reported extensively in recent years, owing to its ability to achieve ordered arrays of nanosize porous channels. As a result, many techniques have been developed to achieve highly-ordered PAA templates by pre-patterning Al foils with hard mold imprint processes. Due to the required pressure of the molds on the Al surface, such processes are not compatible with Al thin films supported on Si - a key development in realizing multi-component layer structures using conventional microfabrication approaches. Of the relatively few reports that have shown long-range ordered PAA on Si, only one demonstrates such order at the wafer-scale to our knowledge¹. Krishnan *et al* reported the formation of highly-ordered PAA arrays formed by pre-patterning the underlying silicon

substrate using interference lithography. The drawback to this approach is that etching directly into the Si substrate precludes functionalization of materials deposited in the pores because a conductive metal layer cannot be incorporated beneath the PAA for electrical contact to the nanoscale devices. In the present work, electron beam lithography is used to pattern the surface of a thin Al layer atop a film of Ti on a Si substrate. The exposed regions of the Al surface are then chemically etched to create dimples that act as initiation sites for pore growth during the anodization process. Square patterned templates with 350nm interpore spacing and 140nm pore width have been achieved. Arrays of hexagonally ordered, circular pores can also be readily fabricated. Both square and hexagonal PAA templates are scalable with customizable long-range order down to an interpore spacing of 45nm with a pore width/diameter of approximately 10nm. By embedding a Fe catalyst within the Al, single walled carbon nanotubes (SWNTs) can be grown within the pores following anodization. The long-range order of the supporting template can allow for the fabrication of vertical SWNT devices in addressable locations using the conductive Ti layer to electrodeposit Pd nanowires in the pores that contact the SWNTs. Ultimately, the realization of long-range order in PAA thin films by chemically etching the Al in patterned locations prior to anodization provides an easily fabricated template for a variety of applications. Currently these templates are being investigated for their use in addressable nanotube field-emission arrays and high-density three-terminal field effect transistors, but may easily be extended to other nanoscale devices as well. ¹Krishnan *et al*, *Nanotechnology*, 2005, 16, 841.

4:10 PM Student

X7, Room Temperature CNT Single Electron Transistor Formed by Plasma Induced Defect Process: Shin Iwasaki¹; Takafumi Kamimura¹; Masatoshi Maeda²; Kazuhiko Matsumoto¹; Noboru Miura³; ¹Osaka University; ²University of Tsukuba; ³Meiji University

Carbon nanotubes (CNTs) are attractive materials for nanoscale devices like single electron transistors (SETs). In the case of quantum dots made in CNTs, the charging energy becomes large due to the small diameter of CNTs. So, they could confine single-electron inside each quantum dot. It is thus possible to form SETs with CNTs (CNT-SETs). So far, the techniques for operating CNT-SET at room temperature (RT) have been reported. Such as AFM nicking of CNTs, thermal chemical process. In this work, we propose the new approach of fabricating CNT-SETs operable at RT. It is the O_2 plasma inducing the defects into a CNT which form potential barriers. The protective film on the CNT is used to attenuate the plasma energy and is imposed the control of a degree of the defects. The sample was prepared as follows. A p-type silicon wafer was used as the substrate with the thermally grown oxide. The catalysts of Si, Mo, Fe were patterned on the SiO_2/Si substrate defined by photolithography and lift off. A CNT was grown by thermal chemical vapor deposition using ethanol as carbon source. After protective film of Ti was deposited on the surface of the sample, Ti/Pt electrodes were deposited on the patterned catalysts. Protective film of TiO_2 was formed by oxidizing the Ti in air. After that, another protective film of SiO_2 (5~58 nm) was deposited on the surface of the sample. Using reactive ion etching, defects were induced in the CNT by O_2 plasma with the fixed condition (O_2 : 60 mL/min, 100 W, 10 sec). Finally, Ti/Pt gate electrode was deposited on the back side of the sample. We term the above process as "Plasma Induced Defect Process". The results we obtained are as follows: (1) the establishment of "Plasma Induced Defect Process", (2) the observation of the electric properties of CNT-SET operable at RT, (3) the control of the inducing defects by the thickness of protective film and (4) the improvement of the efficiency of production of SETs. The CNT-SET has p-type semi-conducting characteristics owing to the O_2 absorption. Though the Coulomb oscillation was observed, it's not periodic due to many quantum dots. Also we investigated the production efficiency of SETs. It is expressed as (the efficiency) = (the number of the formed SET) / (the number of the FET before been induced the defects using O_2 plasma). The highest efficiency obtained is 34 % where the thickness of the protective SiO_2 film is 58 nm. This CNT-SET operable at RT will be the great help for the research of an electric charge sensor like a biosensor.

4:30 PM

X8, Growth of Single and Double-Walled Carbon Nanotubes on a Substrate Using Catalyst Nanoparticles Size-Classified with an Impactor: *Daiyu Kondo*¹; *Shintaro Sato*¹; *Yoshitaka Yamaguchi*²; *Taisuke Iwai*¹; *Yuji Awano*¹; ¹Fujitsu Laboratories Ltd., Fujitsu Limited, Core Research for Evolutional Science and Technology/JST; ²Fujitsu Laboratories Ltd.

Single and double-walled carbon nanotubes (SWNTs and DWNTs) have been attracting a great deal of interest as a candidate for future electronic devices due to their unique physical and chemical properties. Applying them to electronic devices such as high frequency transistors, it is important to control the chirality of SWNTs and DWNTs which determines their electrical features. The diameter-controlled growth of SWNTs and DWNTs is the first step to such control. However, it is difficult to control their diameters using conventional metal films as a catalyst, because catalyst particles formed by annealing metal films have a wide diameter distribution in general. To overcome this problem, size-classified catalyst nanoparticles with a newly-designed impactor¹ were used. This classification method leads to a higher yield of metal catalyst nanoparticles with diameters smaller than 2 nm on a desired substrate in comparison with a method using a differential mobility analyzer.² Growth of SWNTs and DWNTs was performed using size-classified iron nanoparticles as a catalyst by hot-filament chemical vapor deposition (CVD). The particles with various size distributions were produced by laser ablation of iron targets, followed by classification with an impactor. The particles were then deposited on a silicon oxide substrate. As the carbon source, a mixture of acetylene and argon gases was introduced into a CVD chamber, in which the substrate was placed. Hydrogen was also added during the growth and the substrate temperature was 590°C. After the CVD process, carbon nanotubes grown uniformly all over the substrate were observed using scanning electron microscopy. From the Raman spectroscopy and transmission electron microscopy, it was found that high-quality SWNTs were grown from iron nanoparticles with a diameter of around 1.5 nm. Furthermore, radial breathing modes in the Raman spectra show that SWNTs from such nanoparticles have a narrower diameter distribution centering around 1.3 nm than those from metal catalyst films. These results demonstrate diameter-controlled growth of SWNTs with size-classified catalyst nanoparticles. Details will be discussed in the presentation. The authors thank Dr. Naoki Yokoyama, General Manager of Nanotechnology Research Center of Fujitsu Laboratories Ltd. and Prof. Hisanori Shinohara of Nagoya University for their support and useful suggestions. ¹Y. Awano et al., *phys. stat. sol. (a)* 203 (2006) 3611 ²S. Sato et al. *Chem. Phys. Lett.* 382 (2003) 361.

4:50 PM

X9, Late News

Session Y: ZnO: Characterization and Devices

Thursday PM
June 21, 2007

Room: 141
Location: DeBartolo Hall

Session Chairs: Thomas Jackson, Pennsylvania State University; Jamie Phillips, University of Michigan

1:30 PM Student

Y1, Influence of Surface Polarity on the Electrical and Optical Properties of Bulk ZnO: *Martin Allen*¹; *Craig Swartz*¹; *Paul Miller*¹; *Roger Reeves*¹; *Sandeep Chandri*²; *Thomas Myers*²; *Steve Durbin*¹; ¹University of Canterbury; ²West Virginia University

In recent years, ZnO has attracted increased research interest as a potential rival to GaN for opto-electronic applications in the UV range. One outstanding advantage is the ready availability of bulk, single crystal wafers grown using a variety of techniques. Hydrothermal growth typically results in wafers with carrier concentrations of the order of 10^{14} cm⁻³ (300 K) while melt grown wafers have carrier concentrations in the 10^{16} cm⁻³ range. ZnO crystallizes into the wurtzite structure with a large spontaneous polarization,

due to the relatively high ionicity of the Zn-O bond and the lack of inversion symmetry within the crystal. As a result, bound, sheet charges of opposite sign are predicted to occur at the Zn-polar and O-polar faces which may have a significant impact on near surface band bending and carrier distribution^{1,2}. We present the results of a study into the electrical and optical properties of the polar and non-polar surfaces of bulk ZnO using photoluminescence, variable magnetic field Hall effect and Schottky contact characterization. Both hydrothermal and melt grown wafers were investigated. Consistent polarity-related differences were observed in the 4K PL spectra of a large number of hydrothermally grown wafers, in that emission from free exciton recombinations and from a triplet of peaks between 3.3725 and 3.3750 eV were significantly stronger from the Zn-polar face, while emission between 3.3640 and 3.3680 eV was more intense from the O-polar face. These results are broadly consistent with a model of spontaneous polarization induced, near-surface band bending in low carrier concentration wafers^{1,2}. No similar effect was observed in the PL of melt grown wafers^{1,3}, perhaps a result of the higher number of bulk carriers dominating surface effects. The increased importance of surface conduction in hydrothermal ZnO wafers has been confirmed by variable magnetic field and variable temperature Hall effect measurements. Multiple carrier fitting was used to separate the carrier concentration and mobility of bulk and surface carriers with the results explaining the unusually flat mobility versus temperature curves reported for hydrothermal wafers⁴. A method of fabricating high quality Schottky contacts using silver oxide has been developed and was used as another tool to compare the electrical properties of the polar and non-polar faces. A polarity related effect was again observed in hydrothermal wafers, in that laterally homogeneous barrier heights on the Zn-polar face were consistently 130 meV higher than on the O-polar face and 30 meV higher than on m-plane ZnO. These results are again consistent with a spontaneous polarization induced band bending model. ¹Allen *et al.*, *Appl. Phys. Lett.*, in press. ²Harris *et al.*, *Semicond. Sci. Technol.* 15, 413, (2000). ³Chevchenko *et al.*, *Appl. Phys. Lett.*, 89, 182111, (2006). ⁴Look D.C., *Mater. Res. Soc. Symp. Proc.* 957, K08-05, (2006).

1:50 PM

Y2, Using the Exciton Band Edge to Assess ZnO Material Quality and the Effects of Internal and Externally Applied Electric Fields: *John Muhi*¹; *Xiyao Zhang*¹; *Patrick Wellenius*¹; *Anuj Dhawan*¹; ¹North Carolina State University

Most studies assessing ZnO material quality have focused on the structural and electrical properties. In this talk, we focus on using the excitonic absorption edge as a metric since the exciton resonance is a sensitive indicator of material quality. The broadening of the exciton edge has two principle causes: thermal broadening which can be investigated by making absorption measurements as a function of temperature, and broadening induced by internal and external electric field which follows the Dow and Redfield model. Using the Dow and Redfield model the Urbach absorption tail into the band gap can be shown to be due to the effect of microfields that are caused by charged impurities and defects in crystal structure. In this study we have grown a series of ZnO and MgZnO samples under a variety of buffer conditions and show that the quality of the material is directly related to the excitonic absorption features and that this can be quantified using the Dow and Redfield model. This provides a convenient way to optimize ZnO thin films. Furthermore, by constructing a device where high electric fields can be applied across a thin ZnO film the exciton resonance can be directly modulated and the magnitude of internal microfields and externally applied electric fields can be compared.

2:10 PM Student

Y3, Polarization Coupled Response of ZnO-BaTiO₃ Heterojunctions: A Model Approach: *Venkata Voora*¹; *Tino Hofmann*¹; *Matthias Brandt*²; *Mathias Schubert*¹; *Michael Lorenz*²; *Marius Grundmann*²; ¹University of Nebraska-Lincoln; ²Universität Leipzig

Heterojunctions composed of wurtzite-structure ZnO and perovskite-structure BaTiO₃ are very interesting because of the observed ionic lattice charge polarization coupling at their interface, which bears large potential for future device applications. Here we report on polarization hysteresis measurements on ZnO-BaTiO₃ heterostructures with Pt front and back contacts deposited by pulsed laser deposition on (001) silicon substrate. The electrical

data are analyzed using a physical model that accounts for the switchable spontaneous polarization of BaTiO₃ and the non-switchable spontaneous polarization of ZnO. In this model we have implemented a polarization dependent net-interface-charge driven depletion layer, which represents the experimentally observed rectifying behavior of the heterostructure. We find a good agreement between our model generated data and our experiment, and we identify switching voltages and their conditions for the incompletely polarized ferroelectric ionic lattice polarization. We use our model to predict design of such heterostructures for switchable resistance and memory device structures. The influence of physical model parameters on the ZnO-BaTiO₃ heterojunction characteristics will be discussed.

2:30 PM Student

Y4, Annealing Studies on Zinc Oxide Thin Films Deposited by Magnetron Sputtering: *Tingfang Yen*¹; Dave Strome²; Wayne Anderson¹; ¹State University of New York-Buffalo; ²AMBP Tech Corporation

Zinc Oxide has been of interest for applications to optoelectronic devices due to its direct wide bandgap and high exciton binding energy of 60 meV. Hence ZnO could be the ideal potential material for high-speed ultraviolet photodetectors. In this work, we are studying various annealing techniques, including Rapid Thermal Annealing (RTA), Laser Annealing (LA), and furnace annealing on ZnO thin films for modifying electrical properties, which will be applied to the Metal Semiconductor Metal photodetectors (MSM-PD). RTA and LA are attractive in terms of quickness, cost and preservation of companion devices or structures. ZnO thin films were deposited on different substrates, which include glass, silicon dioxide on silicon and silicon, for various studies of optical and electricity properties. RF magnetron sputtering was used for depositing ZnO with a base pressure of 1×10^{-5} Torr, 1 inch diameter ZnO target, two to one ratio of argon and oxygen, and heated substrate. A Ti pump was used before sputtering to reduce moisture and contamination. After RF sputtering, the thin films were annealed in various conditions, RTA 600°C with nitrogen for 1 min, furnace annealing with nitrogen for 30 mins, and laser annealing with 150 mJ/cm². Material properties were examined by Ellipsometry, X-ray Photoelectron Spectroscopy (XPS), Scanning Electron Microscopy (SEM), and conductivity tests with two parallel Ohmic contacts having spacing of 0.2 mm on the ZnO thin films deposited on isolated layers. The refractive index of all samples were found to be around 2.0, the expected value for ZnO. XPS showed a close to 1:1 zinc to oxygen stoichiometry and ZnO has been found at binding energy values of around 530 eV in O_{1s} and around 1020 eV in Zn_{2p_{3/2}}. A worm-like surface structure was observed by SEM. The samples with RTA annealing have the highest conductivity comparing to the other annealing methods and without annealing. MSM-PDs were fabricated using a wide, 6µm, and 2µm spacing of interdigitated Schottky contacts. The film without annealing showed the lowest dark MSM I-V curve and the largest I_{ph}/I_{dark} at 1V. RTA and LA methods are yet to be optimized. Data on pulse response, and MSM performance will be presented.

2:50 PM

Y5, Effects of Electron-Irradiation and Annealing on Deep Centers in Hydrothermal ZnO: *Zhaoqiang Fang*¹; Gary Farlow¹; Bruce Clafflin¹; David Look¹; ¹Wright State University

ZnO substrates can be grown from the vapor phase (VP), melt (MLT), or water solution (hydrothermal, HYD). Unintentionally doped VP and MLT ZnO nearly always have low resistivities (~1Ω-cm at 300 K), due to high concentrations ($10^{16} - 10^{17} \text{ cm}^{-3}$) of shallow donors. In contrast, HYD ZnO typically has much higher resistivities (~200-1000 Ω-cm), because the shallow donors are fully compensated by acceptors (e.g., Li, originally present in the mineralizer), and the electrical properties are controlled by deep donors. Unlike the case in VP or MLT ZnO, we have found that 1-MeV electron irradiation (EI) in HYD ZnO can easily produce semi-insulating (SI) material, with 300-K resistivity $> 10^8 \text{ Ω-cm}$. On the other hand, forming-gas annealing of this irradiated material can reduce the resistivity to about 1 Ω-cm, thus permitting reversible control of resistivity from about 1 to 10^8 Ω-cm . Because deep centers in the high-resistivity irradiated samples cannot be studied by deep level transient spectroscopy (DLTS), we have instead applied thermally stimulated current (TSC) spectroscopy. The HYD ZnO samples used in this study were supplied by Tokyo Denpa and had a typical 300-K resistivity of 210 Ω-cm, carrier concentration of $1.6 \times 10^{14} \text{ cm}^{-3}$, and

electron mobility of 185 cm²/V-s. The electron irradiation was carried out at room temperature using 1-MeV electrons produced by a Van de Graaff accelerator. In as-grown material, the dominant trap present in the TSC spectrum has an activation energy of 0.24 eV and is possibly related to the Li_{Zn} acceptors. However, the EI introduces a new dominant trap, with an activation energy of 0.15 eV, and other traps of energies 0.30 eV, 0.55 eV, and 0.80 eV, respectively. Based on DLTS and other results in the literature, we can speculate on the identities of these centers. For the important EI-induced, 0.15-eV center, we offer two possibilities: (1) V_{Zn}; or (2) Li_{Zn}. The V_{Zn} model has support from positron annihilation experiments, which find V_{Zn} in electron-irradiated material, and density functional theory, which finds a (0/-1) transition near to our 0.15-eV activation energy. On the other hand, the Li_{Zn} model is also intriguing, because neutral Li_{Zn}-H_i complexes form easily if H is present, and the high-energy electrons could remove the H from the complex, as happens with the Mg_{Ga}-H complex in GaN. Further experiments will be necessary to fully identify the 0.15-eV trap.

3:10 PM Break

3:30 PM Student

Y6, Low Temperature PECVD ZnO Thin Film Transistors and Circuits: *Jie Sun*¹; Devin Mourey¹; Thomas Jackson¹; ¹Pennsylvania State University

ZnO is an attractive material for thin film electronics due to its wide bandgap, good electrical transport, and transparency.^{1,2} Recent thin film transistors (TFTs) fabricated using Al₂O₃ as the gate dielectric have demonstrated a mobility of 17.6 cm²/V×s with a threshold voltage of 6 V.³ We report here ZnO TFTs fabricated using ZnO and Al₂O₃ deposited by low-temperature plasma enhanced chemical vapor deposition (PECVD). PECVD has potential advantages for large area, low cost, and high rate deposition and can be used to deposit both doped and undoped ZnO films. Undoped ZnO films were deposited by PECVD at 200°C using diethyl zinc (DEZ) and carbon dioxide (CO₂) gas mixtures. The films are transparent and colorless and x-ray diffraction indicates a c-axis orientation. Room temperature photoluminescence shows a free exciton transition energy of 3.39 eV with a full-width at half-maximum of 160 meV. PECVD ZnO TFTs were fabricated using a bottom-gate structure. 100 nm of Cr was sputtered on a glass substrate as the gate layer and patterned using wet etching. A 150 nm thick Al₂O₃ layer was deposited on the Cr gate by PECVD at 200°C using a trimethyl aluminum (TMA) and CO₂ gas mixture. A 40 nm undoped ZnO film was then deposited on the Al₂O₃ by PECVD from DEZ and CO₂. The same deposition chamber was used for both the Al₂O₃ and the ZnO and the films were deposited sequentially. For TFT patterning the ZnO was etched using dilute HCL and the aluminum oxide was etched using dilute HF. Aluminum source and drain electrodes were then deposited by thermal evaporation and patterned by lift-off. From log(I_D) versus V_{GS} and $\partial I_D / \partial V_{GS}$ characteristics for device at V_{DS} = 20 a field effect mobility $> 10 \text{ cm}^2/\text{V}\times\text{s}$, threshold voltage of 7.5 V, sub-threshold slope less than 1 V/dec, and a current on/off ratio > 104 was extracted. The on/off ratio was limited in part by gate leakage through the Al₂O₃ which also may allow some charging of interface states at the Al₂O₃/ZnO interface. Simple inverter circuits were fabricated with these ZnO TFTs and had acceptable switching characteristics and a peak gain of about 5. This work demonstrates that high mobility ZnO TFTs and simple circuits can be fabricated using ZnO thin films deposited by PECVD at low temperature. ¹R. L. Hoffman, B. J. Norris and J. F. Wager, Appl. Phys. Lett., 82, 733 (2003). ²P. F. Carcia, R. S. Mclean, M. H. Reilly, and G. Nunes, Appl. Phys. Lett., 82, 1117 (2003). ³P. F. Carcia, R. S. Mclean, and M. H. Reilly, Appl. Phys. Lett., 88, 123509 (2006).

3:50 PM Student

Y7, Fabrication and Performance of Zinc Oxide Thin Film Transistors: *Yongwoo Jeong*¹; Tingfang Yen¹; Wayne Anderson¹; ¹University at Buffalo

We present research result on ZnO thin film transistors. Such a device might be useful for integration with a photodetector. A p-type silicon was employed for the base substrate which first went through a basic cleaning process (Acetone-Methanol-DI water). A 150nm thick isolation oxide layer was deposited on the substrate by using plasma enhanced chemical vapor deposition (PECVD). Based on a back gate design, two gate patterns were developed by optical lithography and chromium was evaporated on the gate oxide windows opened by buffered hydrofluoric acid. This was followed by PECVD of a 150 nm gate oxide. The ZnO was deposited by RF magnetron

sputtering from a 1.0 inch diameter target. A base vacuum in the range of 8×10^{-6} Torr was first achieved. The vacuum system is diffusion pumped with an added cold trap and a titanium pump to remove water vapor. Sputtering was done at a power of 100 W in an atmosphere of 15 mTorr O_2 and 5 mTorr Argon. In some cases, the ZnO film was annealed at 600°C in Nitrogen gas at 1 liter/min, for 30 minutes. Finally, source and drain patterns were fabricated and deposited using chromium metal. The channel length and width are approximately 0.006 cm and 0.02 cm that vary in 4 different source/drain dimensions. Achieved transconductance was 2.13×10^{-4} S and field effective mobility at $V_D=7V$ was about $101 \text{ cm}^2/V\cdot\text{s}$. Threshold voltage was 4.2 V and switching on/off current ratio about 2.8×10^4 . Output curves, transfer curves, and structures of thin film transistors are analyzed and compared for ZnO films as deposited, furnace annealed or laser annealed.

4:10 PM Student

Y8, Interface Study of ZnO Nanowire Transistors Using Low-Frequency Noise and Temperature-Dependent I-V Measurements: *Sanghyun Ju*¹; Sunkook Kim¹; Gang Lu²; Antonio Facchetti²; Saeed Mohammadi¹; Tobin Marks²; David Janes¹; ¹Purdue University; ²Northwestern University

Semiconductor nanowire transistors (NWTs) have attracted considerable interest for future electronic and optoelectronic applications. Among the most promising semiconductor nanowire materials, ZnO exhibiting wide bandgap, transparency, tunable surface reactivity, large exciton binding energy and high optical gain has been intensively investigated. High-performance and reliable ZnO NWTs might enable new applications in the area of “invisible” electronics as well as and for bio/chemical sensors, and displays. However, in order to quantify noise and reliability properties required for commercial devices, it is important to investigate nanowire transistors in terms of bias stress and temperature, along with current-voltage characteristics. In this study, we have investigated single ZnO NWTs using nanoscopic self-assembled nano-dielectrics (SANDs) as an organic gate insulator in terms of their low-frequency noise and temperature-dependent current versus voltage (I-V) characteristics. For comparison, ZnO NWTs using SiO_2 as the gate insulator are also studied. The low frequency noise (1/f) spectral density of the ZnO NWTs was measured to evaluate the interface quality of SAND- and SiO_2 -based ZnO NWTs. The amplitude of the current noise spectrum (SI) is proportional to I_d^2 in the transistor operating regime. The inverse noise amplitude is linearly proportional to $|V_g - V_{th}|$, and the slope of $1/A$ vs gate voltage in SAND-based ZnO NWTs is 4 times larger than that of SiO_2 -based ZnO NWTs. The extracted Hooge’s constants (a_H) are $\sim 2.87 \times 10^{-2}$ (SAND-based ZnO NWTs) and $\sim 1.4 \times 10^{-1}$ (SiO_2 -based ZnO NWTs). The lower a_H for SAND-based ZnO NWTs demonstrates the improved SAND/ZnO NW interface quality compared to that of the SiO_2 -based control device. Temperature-dependent I-V studies ($T_s = 25 \sim 125^\circ\text{C}$, 25°C gap) show that the hysteresis of the transfer curves and the threshold voltage shifts of SAND-based ZnO NWTs are smaller than those of SiO_2 -based ZnO NWTs. These results indicate that SAND-based devices exhibit lower interface trap states and defects in comparison to those of SiO_2 gate insulator, and that SAND surface has low net charge trap densities. The results of low-frequency and temperature-dependent I-V measurements verify that NWTs with SAND nanodielectrics are very robust. Channel activation energies extracted from Arrhenius plots of the SAND-based ZnO NWTs provide information about the relative barriers for charge injection into the channel. The activation energy dependence on gate bias indicates that the contact barriers are relatively low, as would be expected for the small offset between the contact metal (Al) workfunction and the calculated bulk Fermi level position for the n-type nanowires.

4:30 PM Student

Y9, Photodetection and Electroluminescence from Optoelectronic Devices Based on Sb-Doped p-ZnO: *Leelaprasanna Mandalapu*¹; Faxian Xiu¹; Zheng Yang¹; Jianlin Liu¹; ¹University of California, Riverside

ZnO has been under extensive research for its potential optoelectronic applications. The intrinsic properties of ZnO such as wide band gap, large exciton binding energy, and high radiation hardness make it an appropriate material for these applications. However, one of the hindrances in the progress of ZnO based devices is the difficulty of reliable p-type doping. Nevertheless, we have succeeded in producing reliable p-type ZnO on Si by using Sb doping in molecular-beam epitaxy recently, and in this presentation,

we report our progress on optoelectronic devices fabricated based on Sb-doped p-type ZnO films. We also discuss about Al/Ti and Au/Ni Ohmic contacts fabricated for improving the device performance. Sb-doped p-type ZnO films were grown on n-type Si (100) substrates. Al/Ti metal was evaporated on the ZnO film and appropriately annealed to fabricate metal-semiconductor-metal (MSM), Schottky and photoconductive detectors. Backside contacts on Si substrate were made to form heterojunction diode. Current-voltage measurements resulted in typical characteristics. MSM devices showed the presence of double barrier while Schottky detectors had rectification of a diode. Photoconductors with Ohmic contacts exhibited a specific contact resistivity of about $22 \Omega \text{ cm}^2$ and interestingly, the heterojunction photodevices behaved like a typical p-type Schottky diode. Good photoresponse in the ultraviolet (UV) region was obtained from all the devices. In addition to ZnO photodetectors, p-ZnO/n-Si LED devices were fabricated. Electroluminescence in the yellow band was observed at different measurement temperatures. Although good preliminary results have been obtained, the performance of the devices was limited by large contact resistance offered by Al/Ti contacts, leading to a shorter lifetime due to heating effects. Therefore, Au/Ni contacts were fabricated on Sb-doped p-type ZnO film owing to larger work function of Au. A specific contact resistivity of $2.8 \times 10^{-4} \Omega \text{ cm}^2$ is achieved, indicating that Au/Ni contacts are more suitable. These results suggest that Sb-doped ZnO on Si is a suitable p-type ZnO film for optoelectronic applications.

4:50 PM

Y10, CdZnO/MgZnO Multilayered Structures for Photonic Application: Growth and Devices: *Andrei Osinsky*¹; Junqing Xie¹; Brian Hertog¹; A. Dabiran¹; Peter Chow¹; J. Mares²; Winston Schoenfeld²; Stephen Pearton³; David Norton³; David Look⁴; John Muth⁵; ¹SVT Associates, Inc.; ²University of Central Florida; ³University of Florida; ⁴Wright State University; ⁵North Carolina State University

Recent progress in the development of ZnO-based materials demonstrates their potential for many important light emitting applications.¹ In this presentation, we discuss the status of high quality epitaxial growth of ZnMgCdO-based thin-layered structures using Molecular Beam Epitaxy with RF-plasma and ozone sources. The nucleation process as well as the evolution of the film growth while controlling the 2D and 3D growth modes are discussed in conjunction with the film crystal quality and fundamental optical properties. Growth experiments using lattice matched ZnO substrates, slightly mismatched GaN templates as well as highly mismatched sapphire substrates are reported. The growth of high crystal and optical quality single layer films and multilayered structures has been confirmed by crystallographic, optical, and electrical measurements. A summary of high resolution X-ray diffraction, SIMS, RBS, optical transmission, photoluminescence, and cathodoluminescence mapping for $Cd_xZn_{1-x}O$ layers with Cd mole fraction up to $x=0.78$ is given. Strong optical emission ranging from UV to yellow will be presented for mole fractions of Cd in the range 0-0.78. The dependence of the optical band gap on the composition of $Cd_xZn_{1-x}O$ alloys as well as band gap bowing parameters is discussed. A strong blue shift in optical emission from CdZnO/ZnO MQW structures was observed due to recombination in localized states. Electrical and optical properties of p-type ZnO doped with N and Sb impurities are summarized. The design and performance of ZnO-based LEDs fabricated using hybrid structures is presented.^{2,3} The film thickness, doping concentration, and composition, which affect the LED functionality (including IQE), are also discussed. An LED device with an optimized CdZnO active layer was fabricated and fully characterized. Also, optical waveguide measurements were performed, demonstrating the potential for use in photonic devices. The reported results demonstrate the great potential of CdZnO/MgZnO-based LEDs for use as a light emitter and, in particular, for solid-state lighting. This work was supported by the Army Research Office under a program monitored by Michael Gerhold and the National Science Foundation. ¹D. P. Norton, Y. W. Heo, M. P. Ivill, K. Ip, S. J. Pearton, M. F. Chisholm, and T. Steiner, *Mater. Today* 7, 34 (2004). ²A. Osinsky, J. W. Dong, M. Z. Kausar, B. Hertog, A. M. Dabiran, P. P. Chow, S. J. Pearton, O. Lopatiuk, and L. Chernyak, *Appl. Phys. Lett.* 85, 4272 (2004). ³*Laser Focus World*, January 2006, A. V. Osinsky et al., 2005 MRS Fall Meeting, paper EE9/FF18.