Technical Program

Session M: Graphene - Materials and Characterization

Thursday AM
June 24, 2010

Room: 102
Location: University of Notre Dame

Session Chairs: Michael Spencer, Cornell University; Randall Feenstra, Carnegie Mellon University

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8:20 AM Invited

M1, Material and Electronic Properties of CVD Graphene Grown on Ni and Cu then Transferred to Insulators: Helin Cao[1]; Qingkai Yu[2]; Luis Jauregui[1]; Deepak Pandey[1]; Robert Colby[1]; Jifa Tian[1]; Nathan Guisinger[3]; Eric Stach[1]; Steven Pei[2]; *Yong Chen*[1]; [1]Purdue Univ; [2]University of Houston; [3]Argonne Nat Lab

We have synthesized large scale (up to several inches) graphitic and graphene thin films by chemical vapor deposition (CVD) on polycrystalline Ni (1,2) and Cu (3) foils and systematically characterized their structural and electronic properties after transferred onto insulating SiO2 (on doped Si) substrates. For films grown on Ni (1,2), structural characterizations by atomic force microscopy (AFM), scanning tunneling microscopy (STM), cross-sectional transmission electron microscopy (XTEM)(4) and spectroscopic Raman mapping confirm that such large scale graphitic thin films contain both thick graphite regions and thin regions of few layer graphene. The films also contain many wrinkles, with sharply-bent tip and dislocations revealed by XTEM, yielding insights on the growth and buckling processes of the film. Measurements on mm-scale back-gated transistor devices fabricated from the transferred film show ambipolar field effect with resistance modulation ~50% and carrier mobilities reaching ~2000 cm^2/Vs. We also demonstrate quantum transport of carriers with phase coherence length over 0.2 µm from the observation of 2D weak localization in low temperature magneto-transport measurements. Our results show that despite the non-uniformity and surface roughness, such large-scale, flexible thin films can have electronic properties promising for device applications. For films grown on Cu (3), we show they consist dominantly of monolayer graphene as indicated by Raman mapping. STM imaging shows monolayer graphene lattice. Low temperature transport measurements are performed on micro devices fabricated from such CVD graphene, displaying ambipolar field effect (with on/off ratio ~5 and carrier mobilities up to ~3000 cm^2/Vs) and "half-integer" quantum Hall effect, a hall-mark of intrinsic electronic properties of monolayer graphene. We also observe weak localization and extract information about phase coherence and scattering of carriers by disorder in the graphene. Finally, we have measured the thermal conductivity of suspended CVD graphene to be ~3000 W/m-K, comparable with that of exfoliated graphene, by combining electronic transport and Raman thermometry (5). 1. Q. Yu et al., Applied Physics Letters, 93, 113103 (2008); 2. H. Cao et al., Journal of Applied Physics, 107, in press (2010) DOI: 10.1063/1.3309018; 3. H. Cao et al., Applied Physics Letters, accepted (2010) (arXiv: 0910.4329); 4. R. Colby et al., Diamond and Related Materials 19, 143 (2010); 5. L. Jauregui et al., ECS Transactions (Proc. ECS-217), in press (2010).

9:00 AM

M2, Fabrication and Characterization of Graphene Materials Grown via CVD on Copper Based Substrates: *Michelle Kelly*[1]; Kristof Tahy[1]; M. Jane Fleming[2]; Barbara Raynal[1]; Vladimir Protasenko[1]; Huili Xing[1]; Debdeep Jena[1]; [1]University of Notre Dame; [2]Saint Mary's College

The exceptional electrical properties of graphene materials have led to an explosion of research investigating graphene's potential as the foundation for a future generation of devices as well as developing methods of producing high quality graphene materials. Material quality and our ability to manipulate graphene's properties will ultimately determine the success of graphene as a device platform. Recently, the formation of single layer graphene via catalyzed-chemical vapor deposition (CVD) on copper foils has generated rapidly a rapidly growing body of research on graphene materials produced by CVD

on copper based substrates.[1] In this work, we explore growth conditions by CVD of graphene on metal substrates with subsequent structural and electrical characterization. We deposit single layer graphene films using catalyzed-CVD on copper foil, evaporated copper films, and copper-nickel alloy substrates. Pre-growth chemical and thermal treatment of the copper catalyst material enables graphene deposition at temperatures ranging from 800-1050 \176C. Following growth, graphene sheets are transferred to a range of host substrates using wet etch methods similar to those described in other work1 or processed in place by undercutting evaporated copper films as demonstrated by Levendorf et.al.[2] Using Raman mapping, we show that we can routinely produce large area single-layer graphene with Raman spectra showing a characteristic 2D:G peak ratio of ~2 that is uniform over large regions. Additional supporting characterization is made using SEM and AFM. One promising future application for graphene materials is in radiofrequency (RF) devices. We have previously reported RF device performance for epitaxial graphene from SiC substrates.[3] RF device characteristics of graphene derived from SiC will be compared to CVD graphene on metal substrates. [1]Li, X., et. al. Science, 324, 1312-1314 (2009). [2]Levendorf, M.P., et.al. Nano Letters, 9, 4479-4483 (2009). [3]Tahy, K., et. al. Conference digest of the 67th DRC(2009).

9:20 AM Student

M3, Kinetic Limitations in the Formation of Graphene on the C-Face of SiC: *Luxmi Luxmi*[1]; Nishtha Srivastava[1]; Patrick Fisher[1]; Randall Feenstra[1]; [1]Carnegie Mellon University

Correlated atomic force microscopy (AFM) and low-energy electron microscopy (LEEM) measurements are used to study the formation of epitaxial graphene on the two different faces of SiC{0001} – the (0001) surface (*Si-face*) and the (000-1) surface (*C-face*). The graphene formation is found to occur in quite different ways in the two cases. For the Si-face, using graphene preparation by annealing the SiC wafer in vacuum, graphene is found to form predominantly in a layer-by-layer mode for graphene thickness greater than 2 monolayers (ML). For thinner graphene, e.g. with an average thickness of 1 ML, vacuum annealing produces considerable inhomogeneity in the thickness, but the use of annealing in an argon environment is found to enable the formation of uniform ML-thick film.[1] Thus, for the Si-face, the techniques for reproducible formation of uniform, constant-thickness graphene films seem to be well in hand. The situation for the C-face is, however, quite different. For one thing, the temperature required for formation of a given graphene thickness, ≈4 ML, on the C-face are about 200°C lower than for the Si-face. We find that this reduction in temperature yields greatly differing motion of surface steps during graphene formation for the two cases. For the Si-face the steps are found to form bunches, separated by typically 10 µm or more, with large, flat terrace separating the bunches. In contrast, for the C-face, motion of steps is limited to a few µm, and we observe in LEEM graphene domains with a wide range of thicknesses and limited in lateral extent to a few µm. This limited motion of the surface steps provides evidence, we believe, of a significant kinetic limitation in the graphene formation for the C-face. We have performed both AFM and LEEM on identical locations of a C-face graphene film, from which we determine *lower surface morphology* on areas having *thicker graphene*, thus also providing evidence for limited kinetics in the graphene formation on the C-face by vacuum annealing. Unlike the situation for the Si-face, we have not thus far been able to produce ML-thick graphene on the C-face using argon annealing; rather, we obtain either very thick films or zero graphene thickness. These studies are continuing, with the use of a disilane environment as an alternative to the argon environment.[2] This work is supported by NSF. [1]C. Virojanadara, M. Syväjarvi, R. Yakimova et. al., Phys. Rev. B 78, 245403 (2008). [2]R. M. Tromp and J. B. Hannon, Phys. Rev. Lett. 102, 106104 (2009).

9:40 AM Student

M4, Graphene to Graphane: Novel Electrochemical Conversion and Possible Applications: *Kevin Daniels*[1]; Biplob Daas[1]; Rui Zhang[1]; John Weidner[1]; Christopher Williams[1]; Tangali Sudarshan[1]; MVS Chandrashekhar[1]; [1]University of South Carolina

Graphene hydride, or better known as graphane is as thermodynamically stable as comparable hydrocarbons, more stable than metal hydrides and more

stable than graphene by ~0.15eV. This along with its large hydrogen storage capacity 7.7 wt%, which exceeds the DOE 2010 goal, also makes it an ideal candidate for hydrogen storage. The difficulty with forming graphane is the need for atomic hydrogen. Techniques implemented by other groups involve in situ development of atomic hydrogen by hydrogen plasma or pumping explosive gases into the furnace. These techniques are costly, dangerous and lack controllability needed for possible device applications. In this paper, we demonstrate an alternative electrochemical means to generate atomic hydrogen, simplifying the synthesis and controllability of graphane formation. On-axis, semi-insulating, 6H-SiC substrates were used to form epitaxial graphene at ~1400°C in vacuum as starting material for graphane production. The ratio of the graphene Raman G-peak to the disorder D-peak was >10, showing the high quality of the starting material. Atomic hydrogen was generated using a home-built electrochemical setup with current applied though a 10% sulfuric acid solution, with a Pt wire and exposed graphene as the anode and cathode, respectively. With this setup, H+ ions are attracted to the exposed graphene. Cyclic voltammetry, with a Hg_2SO_4 reference (0.67V vs. NHE) revealed that this conversion occurs at ~0.2V below the hydrogen evolution potential in water. Using the potential thus determined, conversion to graphane was performed until the conductivity of the graphane decreased to unmeasurable levels. This conversion was confirmed using graphane's known Raman peaks. As expected, there was a sharp increase in the D peak as well as a red shift in the peak from $1340cm^{-1}$ to $1330cm^{-1}$, likely caused by the formation of sp^3 bonds. Another peak at ~$2930cm^{-1}$ was an indication of C-H bonds. A fluorescence background, along with increased SiC substrate signal was also observed in the working area, suggesting the presence of a bandgap in the material. This conversion was distinguished from lattice damage by reversal back to graphene by annealing in argon for 4 hours at 1000°C. The Raman spectra of the area after reversal clearly shows disappearance of the C-H peak at ~$2930cm^{-1}$ showing desorption of hydrogen in the material. The D peak shifted back to pre-conversion state at $1340cm^{-1}$ and fluorescence background was no longer present. While the D and G peaks shifted back to pre-conversion positions, their intensities show that there was some residual damage most likely caused by the strain of the hydrogenation. The conductivity of the graphane samples increased by ~100-1000x from pre-conversion graphene levels, without significant degradation of surface morphology, increase in roughness from 1.04nm to 1.62nm. Further optimization is expected to reduce this residual damage.

10:00 AM Break

10:20 AM

M5, Growth of Few Layer Graphene on C-Face SiC: *Virgil Shields*[1]; MVS Chandrashekhar[1]; Shriram Shivaraman[1]; Michael Spencer[1]; Gary Tompa[2]; Nick Sbrockey[2]; [1]Cornell University; [2]Structured Materials Industries, Inc.

Growth of few monolayer graphene on (0001-bar) SiC has been achieved using a slow cooldown temperature technique. Normal growth on (0001-bar) SiC results in relatively thick graphene comprised of a large number of folds and pores that penetrate the layers compared to thinner (0001) face growth having virtually no folds or pores. The presence of the folds and pores can negatively affect the graphene electrical characteristics and impair potential device performance. This process has resulted in a significant reduction in thickness, folds and pores making the (0001-bar) surface comparable to the (0001) surface. On-axis semi-insulating 6H-SiC was used for graphene growth by thermal decomposition. The surfaces of the SiC substrates were CMP polished only and not hydrogen etched. The (0001-bar) SiC graphene layers were grown at an ultimate temperature of about 1400ºC for 30 minutes at a vacuum pressure in the upper 10^{-6} torr range. The process included a rapid increase to the growth temperature in two steps and a slow cooldown rate of less than 10ºC per minute from the point of growth. Using this process, a reduction in surface roughness from about 23nm (without slow cooling) to less than 2nm (with slow cooling) was achieved. AFM and Raman data was used to determine the thickness of the graphene layers. The morphology was observed to be comparable to that of few monolayer (less than four) graphene on the (0001) SiC face.

10:40 AM

M6, Graphene Growth on SiC, SiO₂, and Sapphire with Carbon Addition: *Jeonghyun Hwang*[1]; Virgil Shields[1]; Chris Thomas[1]; Shriram Shivaraman[1]; Dong Hao[1]; Moonkyung Kim[1]; Michael Spencer[1]; [1]Cornell University

In this study, we report growth of graphene/graphite on SiC, SiO_2, and sapphire using carbon addition technique. The growths were carried out in a conventional cold wall CVD reactor which has been used for SiC epitaxy. On-axis 6H-SiC, SiO_2 on SiC, and sapphire (0001) substrate were heated up (1250°C to 1650°C) under Ar environment (100 to 600 Torr), and propane (C_3H_8) was supplied as a carbon source. The propane was provided as a mixture form (10% propane in Ar) and was thermally cracked at the growth temperature. Typical growth time was 3min to 10min. Raman spectroscopy with 488nm laser was employed to characterize the grown graphene/graphite. Raman spectra clearly showed the signature of multilayer graphene or graphite; G-peak (~$1580cm^{-1}$) and 2D-peak (~$2700cm^{-1}$). Also, disorder related D-peak (~$1350cm^{-1}$) was observed and the ratio of the intensity of D-peak and G-peak (I_D/I_G) varied depending on growth condition. Thickness of graphene was estimated based on the attenuation of Raman signal of substrate. In contrast to thermal decomposition of SiC in which the number of graphene layer is limited by Si evaporation, this carbon addition technique allowed multi-layer graphene or graphite formation on both the Si-face and C-face SiC, and also on SiO_2 and sapphire. The thickness (from 3 monolayer to ~100 monolayer) could be controlled by growth time, propane flow rate, and growth temperature. Thickness increased linearly after first ~3min, but the initial nucleation and growth dynamics are still under investigation. As the flow rate of mixture (propane + Ar) increased from 10sccm to 40sccm, the thickness of graphene increased linearly. The thickness and growth temperature showed exponential relation and this could be explained by propane cracking efficiency. The I_D/I_G decreased from ~0.7 to ~0.4 when growth chamber pressure was 100Torr, as growth temperature increased from 1350°C to 1650°C. By increasing the chamber pressure to 600Torr, the I_D/I_G ratio improved significantly. The ratio decreased to ~0.1 on all the SiC, SiO_2 and sapphire substrate at 1650°C. This indicates that crystallization at high temperature with reduced surface evaporation or decomposition is important to get high quality material. To confirm this graphene or graphite formation is not induced by thermal decomposition on SiC, SiC was heated up under the same condition but without propane flow, which resulted in no signature of graphene/graphite by Raman spectroscopy. Hall measurements with Van der Pauw geometry showed ~100 cm^2/Vsec mobility with 3~4E14 cm^{-2} sheet carrier (electron) density in 5mmx5mm sample. More growth optimization and material characterizations (such as TEM and X-ray) will be performed and presented. Also, growth with different hydrocarbon gas (Acetylene, Ethylene, and Methane) will be investigated and compared.

11:00 AM

M7, Ultrafast Transient Absorption Microscopy Studies of Carrier Dynamics in Epitaxial Graphene: *Libai Huang*[1]; Gregory Hartland[1]; Li-Qiang Chu[1]; L Luxmi[2]; Randall Feenstra[2]; Chuanxin Lian[1]; Kristof Tahy[1]; Huili Xing[1]; [1]University of Notre Dame; [2]Carnegie Mellon University

Energy exchange between the electrons and phonons is particularly important to electron transport, and understanding this process will be vital for the realization of future graphene-based electronics. Epitaxial growth is a very promising approach for practical applications, as it has the ability to prepare graphene on a large scale and supported on a substrate. However, epitaxially grown graphene is highly inhomogeneous, with variations in the sample thickness occurring over length scale of a few micrometers. It is also not clear how substrate interactions affect the carrier dynamics. To pave the road for electronic devices based on epitaxial graphene, characterization methods with high spatial resolution are needed to understand these effects. Here we present transient absorption microscopy as a novel tool to characterize graphene, and to interrogate the charge carrier dynamics. This technique has the ability to directly image carrier dynamics with a diffraction-limited spatial resolution and a time resolution of ~ 200 fs. The intensity of the transient absorption signal is shown to correlate with the number of graphene layers. The carrier cooling exhibits a bi-exponential decay, consisting of an instrument-response limited fast decay time t1 (< 0.2 ps) and a slower decay time t2. The value of t2 was found to increase

with increasing pump fluence. The fast decay is assigned to coupling between the electrons and optical phonons in graphene, and the slower decay is attributed to the hot phonon effect. At high pump intensities the slow decay reaches a limiting value, which is assigned to the relaxation time of the optical phonons. The contribution of the slow component to the overall decay was found to vary with spatial position in the sample. This is attributed to differences in coupling between the graphene and the substrate. Transient absorption images at different delay times also reveal variation in optical phonon lifetime that was not related to graphene thickness. These results point to transient absorption microscopy as a potentially important tool for characterizing the electrical conductivity of graphene through measurement of the lifetime of optical phonon modes excited by charge carrier relaxation.

11:20 AM

M8, Comparison of Graphene Thickness Determination for MBE Grown Graphene on SiC Using Raman, XPS, and TEM: *David Tomich*[1]; John Boeckl[1]; Jeongho Park[1]; John Hoelscher[1]; Larry Grazulis[1]; Kurt Eyink[1]; Chip Claflin[1]; William Mitchel[1]; [1]Air Force Research Laboratory

Graphene's exponential rise in interest since its isolation by Geim et al. in 2004 has led to a plethora of publications using different techniques to determine the number of graphene layers present. The techniques range from the very quick and simple optical interference microscopy for exfoliated graphene on SiO2/Si substrate to the tedious and time consuming sample preparation for Transmission Electron Microscopy (TEM) for sublimation grown graphene on SiC. Raman spectroscopy is one of the most reported tools used to determine graphene thickness due to its ease of use, non-destructive nature and wide availability. Raman spectroscopy has been used extensively over the past few decades to study carbon based materials, so the study of this perfect two dimensional form of carbon with Raman is a natural application. Several methods have been used to glean information from the Raman spectrum to relate the number of layers or quality to the electronic properties. We have examined several of these methodologies along with photoelectron spectroscopy and TEM in order to determine an accurate, consistent and rapid process to guide our graphene growth experiments. We have examined x-ray photoelectron spectra (XPS), confocal Raman spectra and TEM images from portions of the same sample in an effort to determine the relative accuracies of these techniques. Growths were conducted in an EPI (Veeco) 930 MBE tool with a modified graphite heater to facilitate growth temperatures up to 1600°C. Films were grown on the chemical-mechanical polished (CMP) Si-face of 6H SiC semi-insulating substrates diced into 10 x 10 mm2 samples. Atomic force microscopy images of the growths indicate good step flow growth with RMS roughness less than 5 nm over 20 x 20 µm2.

11:40 AM
M9, Late News

Session N: Molecular Electronics and Chem / Bio Sensors

Thursday AM   Room: 126
June 24, 2010   Location: University of Notre Dame

Session Chairs: Takhee Lee, Gwangju Institute of Science and Technology; Jay Gupta, Ohio State University

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8:20 AM

N1, STM Studies of Hybrid Inorganic-Organic Molecular Magnets on an Ultrathin Insulating Film: *Taeyoung Choi*[1]; Jay Gupta[1]; [1]Ohio State University

The interplay of electronic structure and magnetic properties has been of interest in various organic materials. For example, transition metal -- tetracyanoethylene (TCNE) complexes form a family of organic magnets with Curie temperatures exceeding room temperature. TCNE has a strong electron affinity that facilitates chemical bond formation and charge transfer with metals. However, the chemical bonding and its influence on electronic and magnetic properties is not well understood at the atomic scale. We use scanning tunneling microscopy to build Co-TCNE and Fe-TCNE complexes with atomic manipulation on an ultrathin insulating layer (Cu2N on Cu(100)). Cu2N decouples the complexes from the conducting substrate, which impacts their electronic and magnetic properties. Tunneling spectroscopy on the complexes shows molecular orbitals and inelastic steps due to various vibrational modes and spin excitations. The degree of charge transfer between single magnetic atoms and molecules could explain the observed difference in energies of these steps among the complexes. The ability to connect such complexes with additional metal atom chains provides an opportunity to study spin and charge transport through single molecules with atomically precise contacts.

8:40 AM Student

N2, Effect of Molecular Tilt Configuration and Interface Dipoles on Molecular Electronic Conduction: *Gunuk Wang*[1]; Tae-Wook Kim[1]; Jamin Ku[1]; Seok-In Na[1]; Gunho Jo[1]; Yonghun Kim[1]; Yun Hee Jang[1]; Dong-Yu Kim[1]; Takhee Lee[1]; [1]GIST

Controlling the charge transport characteristics through molecules between electrodes is important for understanding basic conduction mechanism and realizing potential device applications of molecular electronic systems. The charge transport characteristics in molecular junctions are influenced by molecular structure, metal-molecule contact, conformational effect, and energy level alignment of molecular orbitals with the Fermi levels of the electrodes[1,2]. We investigated the effect of the molecular configuration on the electronic transport in molecular junctions where the molecular configuration is controlled by conducting atomic force microscopy (CAFM)2. Our results indicate that the degree of tilting of alkanemonothiol molecules enhances chain-to-chain intermolecular charge transfer, so called through-space tunneling. We will show inflection points on a plot of ln $(J/V2)$ vs $1/V$ with various tip-loading force of CAFM, consistent with the transition of the electronic transport mechanism from direct tunneling to Fowler-Nordheim tunneling[3]. Also, we will discuss recent results about the energy level alignment of molecular electronic devices with organic interlayer (PEDOT:PSS) by interface molecular dipoles. We demonstrate that the molecular orbital levels relative to the electrode's Fermi level shift to higher or lower energies according to the direction of the dipole moments at the junction interface when the junction temperature is increased. [1] G. Wang et al. Phys. Rev. B 76, 205320 (2007). [2] G. Wang et al. J. Am. Chem. Soc 131, 5980 (2003). [3] J. M. Beebe et al. Phys. Rev. Lett. 97, 026801 (2006).Acknowledgement: the National Research Laboratory Program, the National Core Research Center grant, the World Class University program of the Korean Ministry of Education, Science and Technology of Korea, and the Program for Integrated Molecular System at Gwangju Institute of Science and Technology.

9:00 AM Student

N3, Improvement of Transfer Characteristics in Carbon Nanotube Field-Effect Transistors with Au Nano Clusters: *Yasuki Yamamoto*[1]; Yasuhide Ohno[1]; Kenzo Maehashi[1]; Kazuhiko Matsumoto[1]; [1]Osaka University

During the past few years, carbon nanotubes (CNTs) have emerged as highly promising components of nanoscale electrical and electrochemical devices. In particular, carbon nanotube field-effect transistors (CNTFETs) have been extensively studied and have been expected for the highly sensitive and label-free biosensors. To increase sensitivity of CNTFET sensors, many unique techniques have been developed. Recently, CNTFETs decorated with metal particles has attracted strong interest. In device fabrication process, the method of depositing metal particles over the entire surface of CNTFETs is usually used. However, the current reduction and noise increase due to the induced defects and screening effect are crucial problems. In this study, we report the marked improvement of transfer characteristics in CNTFETs decorated with Au nano clusters. A decoration process of Au nano clusters was optimized, and additional electrical heating process was adopted to improve transfer characteristics. CNTs were synthesized on Si wafer covered with thermally grown SiO_2 layer via chemical vapor deposition method using patterned Co catalyst with ethanol as a source gas. After the growth of CNTs, 3-Å-thick Au nano clusters were deposited onto

entire device using an electron beam evaporator. Finally, 1 nm Ti and 40 nm Au pads as source and drain electrodes were formed. The channel length of devices was 3µm. Following the device fabrication, the electrical heating process was carried out. CNTFETs with Au nano clusters were electrically annealed by applying high voltage between source and drain electrode at the fixed back-gate voltage of 10 V. This electrical heating process affects the transfer characteristics in CNTFETs strongly. The marked increase in the drain current and improvement of transconductance were observed after the electrical heating process. This improvement in transfer characteristics by electrical heating was not observed in CNTFETs fabricated by conventional Au-decoration process. Therefore, this phenomenon was attributed to the combination of proposed structure and electrical heating process. It is expected that our CNTFETs with Au nano clusters are useful for sensor application.

9:20 AM

N4, Carbon Nanotube Field-Effect Transistor Biosensor with Schottky Barrier Control Gate Electrode: *Masuhiro Abe*[1]; Katsuyuki Murata[2]; Kazuhiko Matsumoto[3]; [1]National Institute of Advanced Industrial Science and Technology; [2]Core Research for Evolutional Science and Technology, Japan Science and Technology Agency; [3]The Institute of Scientific and Industrial Research, Osaka University

The carbon nanotube field-effect transistor (CNT-FET) is expected to be used in several applications. In particular, CNT-FET-based biosensors have been attracted because of its high sensitivity and stability. We have established CNT-FET biosensor and have succeeded detecting proteins [1, 2] and have clarified that the structure of the CNT-FET influenced the sensitivity of the biosensors [3]. In this study, we newly prepared a new structured CNT-FET for a biosensor. The performance as the biosensor of the new CNT-FET was compared with our traditional CNT-FET. In our new structured CNT-FET, the CNT channel is covered by insulator, and the gate electrode is placed above the interface of CNT channel and source-drain electrode. On the other hand, in our traditional CNT-FET, gate electrode is placed all round under the insulator. By using the new CNT-FET, Schottky barrier between the CNT channel and the source-drain electrode is independently controlled at the CNT-FET. In this paper the gate electrode of the new structured CNT-FET is called "Schottky gate electrode". The Schottky gate voltage affected only the interface between CNT channel and drain source electrode and not effected the part of CNT under the sensing area of the CNT-FET biosensor. Therefore, the biosensor of the new CNT-FET has a possibility that have higher sensitivity than our traditional one. For the measurement, a silicone rubber pool was placed around the sensing area of the CNT-FET. 0.1 M Tris buffer (pH = 8.0) was poured onto the CNT-FET and drain current was measured. Drain voltage, electrolyte voltage and Schottky gate voltage were controlled during the measurement. The dependence of the drain current (ID)-electrolyte gate voltage (VEG) properties on the Schottky gate voltage (VSG) was measured. The transconductance at VD = 0.1 V and VEG = +0.4 V were 22.6 nS, 7.6 nS and 4.7 nS when Schottky gate voltage were VSG = +3 V, VSG = 0 V and VSG = -3 V, respectively. Therefore we succeeded in controlling current properties of CNT-FET in the solution by controlling Schottky barrier of CNT-FET. [1] M. Abe, K. Murata, A. Kojima, Y. Ifuku, M. Shimizu, T. Ataka, and K. Matsumoto: J. Phys. Chem. C, 111 (2007) 8667. [2] M. Abe, K. Murata, T. Ataka, and K. Matsumoto: Nanotechnology, 19 (2008) 551. [3] M. Abe, K. Murata, T. Ataka, and K. Matsumoto: J. Appl. Phys., 104 (2008) 104304.

9:40 AM Student

N5, Breakdown Statistics and Nanowire Device Integration of Self-Assembled Nano Dielectrics: *Ruth Anne Schlitz*[1]; KunHo Yoon[1]; Sara Renfrew[1]; Lisa Fredin[1]; Young-Geun Ha[1]; Tobin Marks[1]; Lincoln Lauhon[1]; [1]Northwestern University

Self-Assembled Nano Dielectrics (SANDs) are high-K molecular dielectrics grown by low-temperature solution processes. They offer great potential to enable high-performance electronics on unconventional substrates that are incompatible with the harsh conditions of conventional semiconductor processing. Furthermore, they have already been incorporated into a variety of devices incorporating both inorganic and organic components. However, if

SANDs are to be scaled up successfully, they must have two characteristics: (1) they must be uniformly pinhole free on the scale of the device channel and (2) they must retain properties after device fabrication and processing. To this end, we present a failure analysis of SANDs, utilizing Weibull statistics to empirically determine a critical defect density in SANDs. Our quantitative failure analysis correlates synthesis conditions to the resultant Weibull slopes; typical ß values found are between 3 and 15. By comparison, reported ß values for other inorganic high-K dielectrics are on the same order, with reported values for many dielectrics typically less than 5, but as high as 14.4 for HfO2. Our studies of processing conditions qualitatively show the effects of post-synthesis processing on the SAND; while electron-beam lithography slightly degrades the performance of SAND, the resultant leakage current densities still compare favorably with inorganic dielectrics. Surprisingly, high-temperature anneals up to 400°C reduce the leakage current densities through the SAND and widen the range of processing conditions possible for a SAND device. We will discuss how the synthesis conditions of the SAND and subsequent processing of the parallel-plate capacitors used for the measurement influence the characteristic breakdown behavior. We also correlate these statistics with film morphology and capacitance. Finally, we present results from SAND integrated as a top gate dielectric in silicon nanowire transistors.

10:00 AM Break

10:20 AM

N6, Functionlization Studies on GaN Nanowires: *Devin Rourke*[1]; Christopher Dodson[1]; Aric Sanders[1]; Kristine Bertness[1]; Norman Sanford[1]; [1]NIST Boulder

We have fabricated and tested GaN nanowire bioFETs utilizing amine-reactive surface chemistry, and taken electrical measurements at various stages throughout the functionalization process. Test structures were fabricated with nanowires grown on Si with MBE. GaN nanowires were released into a suspension via ultrasonic agitation, pipetted onto pre-deposited Ti pads and aligned with dieletrophoresis, forming a two-terminal bridge structure. A capping layer of Ti/Al pins the wires to the substrate and forms two conformal electrical contacts. From this point, the most critical requirements for nanowire-based bioFET fabrication are electrical stability and effective surface functionalization. We have demonstrated the electrical stability of these two-terminal GaN nanowire bridge structures when submerged in solutions of pH 1, 4, 7 and 10. We attribute this stability to the inert, chemically robust GaN crystal structure. In addition, leakage current through the solutions was found to be approximately 1nA which is on average 10^5 times less than the current through the nanowire device. We demonstrate via fluorescence microscopy the amine-reactive surface functionalization of GaN nanowires. The preparation scheme utilizes successive wet chemical treatments, allowing on-chip functionalization of pre-fabricated bridge-type nanowire structures. We present strong evidence that piranha etch increases the concentration of reactive hydroxyl groups on the nanowire surface, increasing conjugation of methyl-terminated silane molecules (aminopropyltrimethoxysilane [APTMS]). We have collected I-V data from devices before and after silanization which indicate a 1.5x resistance increase with the deposition of silane. An amine-reactive rhodamine-derivative fluorescent dye is then reacted with the silane molecule, allowing for fluorescence imaging using a confocal scanning laser microscope (CSLM). The degree of functionalization is quantified by the intensity of fluorescence, calculated using selective area image processing and reported as pixel counts above background. We have thus demonstrated an electrically stable, amine-reactive, GaN nanowire-based device structure suitable for bioFET development. The photolithography process allows for integration into massively arrayed IC devices, and on-chip, post-processing functionalization provides flexibility of choice between other functionalization schemes yet to be developed.

10:40 AM Student

N7, Olefin Metathesis Reaction on GaN (0001) Surfaces: *Matthew Makowski*[1]; Dmitry Zemlyanov[2]; Albena Ivanisevic[1]; [1]Weldon School of Biomedical Engineering, Purdue University; [2]Birck Nanotechnology Center, Purdue University

An essential step towards designing new and versatile biosensors is to validate new methodologies for the attachment of biomolecules to the surface.

Gallium nitride (GaN) offers a number of promising properties for novel microfabricated sensors. A surface modification scheme was characterized using X-ray Photoelectron Spectroscopy (XPS) to adapt GaN for use in biosensors. Wafers of undoped GaN (0001) on sapphire were etched in boiling 2 M KOH for 5 minutes to remove the oxide layer. The exposed gallium atoms on the surface were covalently bound to hydrogen through a hydrogen plasma treatment. The wafers were subsequently passivated with chlorine in a solution of phosphorus pentachloride and benzoyl peroxide in chlorobenzene at 90°C for 30 minutes. An alkene termination on the surface was then achieved in 2 M allylmagnesium chloride in tetrahydrofuran at 55°C for 30 minutes. The surfaces were next primed for olefin metathesis by 13.8 mM first generation Grubbs catalyst in dichloromethane at 35°C for 30 minutes. The first run of the scheme resulted in the binding of an amine group by olefin metathesis through 0.5 M allylamine in dichloromethane at 35°C for 30 minutes. The second run consisted of 0.5 M 7-bromo-1-heptene in dicholoromethane at 35°C for 2 hours. The bromine served as a label for XPS to verify the binding of the hydrocarbon to the surface. A microfluidic chip composed of polyetheretherketone was constructed and implemented for the alkene termination, Grubbs priming and olefin metathesis reactions. This resulted in a decrease in reagent volumes and wafer handling. Following each surface termination step, XPS analysis identified the chemical species at the surface. The absence of a shoulder on the Ga 2p peak for the chlorine-terminated and bromine-terminated samples indicates that no substantial oxidation of the surface occurred following the passivation with chlorine and throughout the duration of the scheme. The Cl 2p spectrum is composed of a pair of doublet peaks. Gallium to chlorine bonds produced the doublet with the greater binding energy. The peak within the C 1s spectrum at 280.9 eV signifies the presence of the ruthenium within the Grubbs catalyst following the priming of the surfaces with the olefin metathesis catalyst. The single Br 3d peak indicates the presence of bromine on the GaN surface following the linkage of 7-bromo-1-heptene via olefin metathesis. The final bromine surface coverage was 4.0% of a monolayer. The demonstrated scheme is greatly versatile due to the Grubbs catalyst allowing for a wide variety of alkene-terminated molecules to covalently bind to the GaN surface via olefin metathesis. Future applications of this scheme toward the development of novel biosensors include the binding of peptides, proteins, or antibodies to GaN electronic devices.

11:00 AM Student

N8, Protection of ZnO Nanowires for Liquid-Phase Sensing: *Ashley Mason*[1]; Chien-Chih Huang[1]; Saki Kondo[1]; Myra Koesdjojo[1]; Vincent Remcho[1]; John Conley[1]; [1]Oregon State University

The use of metal-oxide nanowires (NWs) for sensing applications has become a highly active area of research in recent years as the high surface to volume ratio of NWs promises increased sensitivity to a target species. There are many challenges to NW sensing. Important considerations include the problem of device formation using cylindrical NWs and sensor selectivity, sensitivity, stability. High yield fabrication of NW devices and sensors requires alignment of the NWs to previously patterned lithographic features. In this work, directed growth and integration of ZnO nanobridge devices into an electrically accessible three-terminal device structure was achieved using photolithographically pre-patterned carbonized photoresist (C-PR) without the use of a metal catalyst, seed layer, or "pick and place". Electrical measurements of three-terminal field effect NW devices indicate bottom gate modulation of the conductivity of the n-type channel and Schottky type contact between the C-PR and the ZnO nanobridges. We demonstrate that these devices exhibit good ultraviolet (UV) sensitivity and gas phase sensitivity to O2 and humidity. In order to demonstrate selectivity, the strong bonding between biotin and streptavidin can be exploited. The functionalization of ZnO NWs with biotin is mainly controlled by the pH, with deionized (DI) water used as a carrier medium for the biomolecules. However, it is known that ZnO is soluble in H2O and we find that biotin coated ZnO NWs are dissolved completely within 24 hours. Demonstration of selective sensing using ZnO NWs in the liquid phase therefore requires a way to prevent the ZnO from dissolving. In this work, we examine ways to protect ZnO nanowires (NWs) during liquid-phase sensing. We demonstrate a possible coating used to protect the ZnO NWs during submersion in DI water. In one experiment, the contact angle of a DI water droplet was measured as a function of time for ZnO NWs functionalized with either biotin or or the protective coating. While the biotin coated sample exhibited a small contact angle immediately after the H2O droplet was applied, the protected ZnO NW samples showed strong a hydrophobic property. In another experiment, biotin and protected ZnO NW samples were soaked in DI water for 24 hours and monitored via dark-field microscopy. Whereas the biotin coated NWs were dissolved overnight, the protected NWs appeared to remain unchanged. ZnO nanobridge devices with the additional protective coating will be characterized for sensitivity to UV and O2. Demonstration of liquid-phase selective sensing is still underway.

11:20 AM Student

N9, Signal-to-Noise Ratio Improvement of Magnetoelectric Laminate Sensor by Multilayer Structure and Direct Integration with Advanced Microelectronics: *Zhao Fang*[1]; Ninad Mokhariwale[1]; Feng Li[1]; Suman Datta[1]; Qiming Zhang[1]; [1]The Pennsylvania State University

Magnetoelectric (ME) effect is the appearance of an electrical signal upon applying a magnetic field H and/or the appearance of a magnetic signal upon applying an electric field E. This has attracted a lot of interest because the materials featuring the ME effect have potential to be used as high sensitivity magnetic sensors, electrical current sensors, and other devices. Although the ME effect was first observed in single phase materials (e.g. Cr2O3), the composite laminates of the magnetostrictive layer (e.g. Terfenol-D and Metglas) and the piezoelectric layer (e.g. Pb(ZrTi)O3 (PZT), Pb(Mg1/3Nb2/3)O3-PbTiO3 (PMN-PT), and Polyvinylidene fluoride (PVDF)) have attracted much attention due to the strong coupling effect between the magnetostrictive and piezoelectric layers, which derive large ME response at room temperature. The principle of composite laminates is that a magnetic field induces a strain in the magnetostrictive layer by magnetostriction, and the strain is coupled to the piezoelectric layer, resulting in an electric polarization. Strain coupling requires suitable combination of magnetostrictive and piezoelectric layers for efficient displacement transfer. Among the ME composite laminates which exhibit large ME coupling coefficients, the ones with Metglas are particularly attractive due to their low saturation magnetization field and consequently a relatively low dc bias magnetic field (<20 Oe), which is highly desirable for high sensitivity magnetic sensors. In this paper, Metglas and PVDF are used as the magnetostrictive and piezoelectric layers respectively. To realize the applications for medical and life science research, it is desirable for ultra sensitive magnetic sensors to be highly sensitive, miniaturized, low-cost, and easy to operate. Successful exploitation of magnetic sensors is often inhibited by the presence of large volume of sensors and parasitic effects such as environmental noise and parasitic capacitances. In order to mitigate these problems, it is important to integrate the magnetic sensor with the signal conditioning circuitry as directly as possible. To obtain the electric signal from the piezoelectric layer, a custom-made charge mode read-out circuit is used to maximize the signal-to-noise ratio (SNR) and avoid the effect of stray capacitances. For charge mode read-out circuit, the noise analysis shows that the SNR is proportional to the square root of capacitance of the piezoelectric layer, which is confirmed by the experimental results in this paper. A multilayer structure for the piezoelectric layer is employed to increase the sensitivity without increasing the size of the sensor. Since the elastic modulus of Metglas (100-110 GPa) is much higher than that of PVDF (1-3 GPa), it's possible for one Metglas layer to drive multiple PVDF layers. Also the SNR for the custom-made charge mode read-out circuit is compared with that of a commercial charge amplifier.

11:40 AM
N10, Late News

Session O, SiC: Characterization and Growth

Thursday AM
June 24, 2010

Room: 129
Location: University of Notre Dame

Session Chairs: Robert Stahlbush, Naval Research Laboratory; Brett Hull, Cree, Inc.

8:20 AM

O1, Analysis of Dislocation Interactions in Low Dislocation Density, PVT-Grown, Four-Inch Silicon Carbide Single Crystals: *Michael Dudley*[1]; Balaji Raghothamachar[1]; Shayan Byrappa[1]; Gloria Choi[1]; [1]State University of New York at Stony Brook

Synchrotron White Beam X-ray Topography studies are presented of dislocation behavior and interactions in a new generation of one hundred millimeter diameter, 4H-SiC wafers grown using Physical Vapor Transport under specially designed low stress conditions. Such low stress growth conditions have enabled reductions of dislocation density by two or three orders of magnitude compared to the lowest previously reported levels. For example, detailed analysis of transmission geometry topographs recorded from wafers ranging in thickness from four hundred to seven hundred microns demonstrates extremely low defect basal plane dislocation (BPD) densities of just a few hundred per square centimeter on average (these are "true" dislocation densities computed by dividing measured dislocation line lengths from transmission topographs by the imaged crystal volume). Lowering of dislocation densities to such levels provides a unique opportunity to discern the details of dislocation configurations and interactions which were previously precluded due to complications of image overlap at higher dislocation densities. Among the phenomena observed in these studies is the conversion of non-screw oriented glissile BPDs into sessile threading edge dislocations (TEDs). This is observed to provide pinning points for the beginnings of the operation of single ended Frank-Read sources. In some regions, once converted TEDs are observed to re-convert back into BPDs, most probably through overgrowth by macrosteps. This can occur repetitively in a process which provides multiple BPD pinning points. Detailed models for such behavior will be discussed in detail. Detailed topography analysis will also be presented of the deflection of other threading defects into the basal plane which produces complex faulted defect configurations. Models for the creation of such deflected defect configurations will be presented and discussed. The implications of such substrate defect configurations on subsequently grown homoepitaxial layers and the prospects for further defect density reduction to unprecedented levels for Physical Vapor Transport grown SiC will be discussed.

8:40 AM

O2,   Formation of a (5-1)-Bilayer-Height Complex Step-and-Terrace Structure on 4H-SiC (0001) by a Spiral Etching Process: *Jun Suda*[1]; Tsunenobu Kimoto[1]; [1]Kyoto University

We found a very unique step-and-terrace structure on 4H-SiC (0001) surfaces after high-temperature gas etching. Commercially available 2-inch n-type 4H-SiC (0001) just-oriented Si-face substrates were subjected to high-temperature gas etching, which was carried out by using a low-pressure hot-wall chemical vapor deposition system. The etching conditions were as follows: 120 min etching at 1550°C with a hydrogen gas flow of 30 slm and pressure of 20 Torr. The unique step-and-terrace structure consists of a periodic array of pairs of 5-bilayer (BL)-height step and opposite-signed 1-BL-height step. The separation of 5-BL-height and 1-BL-height steps was 200 nm. We revealed that the "(5-1)-BL-height step-and-terrace structure" were continuously generated by a spiral etching process at a screw-type threading dislocation. At the center of spiral pit, one 4-BL-height step appeared, indicating that the threading dislocation has Burgers vector of 1c. However, at very near the center, the 4-BL-height step was decomposed into a 5-BL-height step and an opposite-signed 1-BL-height step. Note that total step height was conserved, i.e., 4 BL. The pair of 5-BL-height and 1-BL-height steps formed a spiral pit. At the outside of spiral pit, the periodic array of (5-1)-BL-height step pairs was observed. It should be

noted that some of spiral pits on the same 4H-SiC substrate did not have such a complex structure. They consisted of double spiral of 2-BL-height step, which are generally observed on 4H-SiC (0001) surface after etching. The author also investigated spiral etching of 6H-SiC (0001). In the case of 6H-SiC, only double spiral of 3-BL-height step was observed. We concluded that the core structure of spiral pit is the key to form the unique step-and-terrace structure. A mechanism for step-flow etching which conserves the step pairs is also discussed.

9:00 AM

O3, Processes Controlling the Carrier Lifetime in n⁻ 4H-SiC Epilayers with Low $Z_{1/2}$ Concentrations: *Paul Klein*[1]; Rachael Meyers-Ward[1]; K.-K. Lew[1]; Brenda VanMil[1]; C.R. Eddy[1]; D.K. Gaskill[1]; A. Shrivastava[2]; T.S. Sudarshan[2]; [1]Naval Research Laboratory; [2]University of South Carolina

The ability to grow epitaxial layers of 4H-SiC with low concentrations of the Z1/2 defect, the bulk defect that limits the lifetime in this material, has resulted in measureable increases in the observed lifetimes. However, achieving the even longer lifetimes necessary for very high voltage switching devices and for lifetime control requires an understanding of the recombination processes that limit the carrier lifetime in these low-$Z_{1/2}$ materials. In this work, differences in the temperature dependence of the lifetime for different recombination mechanisms have been employed to identify the process that controls the carrier lifetime in these materials. The temperature dependence of the carrier lifetime was measured at low injection for several low-$Z_{1/2}$ epilayers over a wide temperature range and compared to simulations. The bulk lifetime is expected to be slow-varying until the temperature becomes high enough to thermalize carriers that are trapped on deep defects back into the bands. Then the lifetime increases in a thermally activated manner with temperature, with the activation energy reflecting the depth of the trap. Surface recombination was modeled based on existing approximations to the solution of the one dimensional diffusion equation, taking into account recombination at the sample surface and at the substrate/epilayer interface. The simulated carrier lifetime is the sum of terms due to carrier diffusion to the surface and carrier capture at the surface, so that the slowest mechanism is the rate-limiting process. Surface capture at low injection leads to a thermally activated decrease in the lifetime with temperature due to surface band-bending, while at higher temperatures the diffusive component dominates and results in a power-law increase in the lifetime, following the temperature dependence of the diffusion coefficient. Due to the existence of the space charge region formed at the n_+/n_- interface, minority holes are repelled from the interface and the corresponding surface recombination velocity is greatly reduced. The behavior of surface recombination at high injection levels becomes distinctly different, as the band bending at the surface and at the interface disappears when the system is driven into flat-band conditions. The experimental results are consistent with carrier lifetimes dominated by surface recombination. No significant contribution from other bulk defects was observed, and upper limits to the bulk recombination rate were determined to be consistent with the measured $Z_{1/2}$ concentrations in these materials. There was also no discernable contribution from carrier capture at the epilayer/substrate interface. These results were found to be consistent with behavior expected under low injection conditions for epilayers grown on n_+ substrates.

9:20 AM

O4, Comparative Studies of Carrier Dynamics in 3C-SiC Layers Grown on Si and 4H-SiC Substrates: *jawad ul hassan*[1]; Patrik Scajev[1]; Kestutis Jarasiunas[1]; Masashi Kato[2]; Anne Henry[3]; Peder Bergman[3]; [1]Vilnius University; [2]Nagoya Institute of Technology; [3]linköping University

Large lattice mismatch and different thermal expansion coefficient leads to high structural defect density in 3C-SiC layers grown on Si substrates (3C/Si). These extended defects severely deteriorate optical and electrical properties of the crystal. Heteroepitaxial growth of 3C on hexagonal 4H-SiC substrates (3C/SiC) could be beneficial to avoid growth induced extended defects and hence may result in superior crystalline quality. We performed comparative studies of optical properties and carrier dynamics in 3C-SiC layers grown on Si and SiC substrates using three optical techniques. 3C-SiC n-type layers (nitrogen doping ~ $1x10^{17}$ cm⁻³ and thickness of ~ 300 µm) were grown on undullant Si substrates and free standing 3C layers were obtained after mechanically

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polishing away Si substrate. Low doped n-type layers (nitrogen doping ~ 1 x 10^{15} cm^{-3} and thickness of ~ 100 μm) were grown on nominally on-axis 4H-SiC substrates using horizontal hot-wall chemical vapor deposition reactor in Linköping university. Important electronic parameters for 3C-SiC, such as carrier lifetime, diffusion coefficient and diffusion length were determined using different optical techniques. These included light diffraction on transient free carrier grating (TG), free carrier absorption (FCA) and time-resolved photoluminescence (TRPL). The measurements were made over a wide range of excess carrier densities, $\Delta N = 10^{16} - 10^{19}$ cm^{-3}, and temperatures, T = 80 - 800 K. The carriers were excited by a frequency tripled Nd:YLF-laser at 351 nm. Low temperature photoluminescence spectroscopy was also performed to observe the purity of the material. PL spectra at 5 K revealed similar features in both layers over wide energy range. The near band edge emission was dominated by nitrogen-bound exciton recombinations while very weak DAP transitions were observed at lower energies. In contrary, FCA decay kinetics provided very different carrier lifetimes of 16 ns in (3C/Si) layers and 100 ns in (3C/SiC) layers at room temperature, thus indicating higher structural quality of on-axis grown 3C/SiC layers. We note a long lifetime of ~130 ns at the backside of free standing 3C/Si layers (nearby 3C/Si interface). A higher density of SFs has been reported in this region; however, the origin of so long lifetime in high SF density region is not known. In the 3C/SiC layers, the temperature dependence of carrier lifetime in 80-800 K range revealed non-monotonous increase of lifetime from ~50 ns to ~300 ns. The TG decay times in both layers revealed similar D(T) dependences in 80-800K range, with bipolar mobility values of 140-160 cm^2/Vs at RT. The mobility and lifetime data in 3C/SiC layers provided carrier bipolar diffusion length of ~6.5 μm and hole diffusion length of ~4.5 μm, being the largest values reported up to now for 3C.

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O5, Expansion and Contraction of Stacking Faults in 4H-SiC: *Nadeemullah Mahadik*[1]; Robert Stahlbush[1]; Joshua Caldwell[1]; Karl Hobart[1]; [1]Naval Research Laboratory

Silicon Carbide (SiC) power devices such as p-i-n diodes, gate turn off thyristors, and bipolar junction transistors are known to have serious forward voltage degradation due to the expansion of Shockley type stacking faults (SSF) created by basal plane dislocations (BPD) in the 4H-SiC epilayers [1,2]. Initially, it was thought that these SSFs only expanded and never contracted in power devices. Recently, a contraction of SSFs was observed [3] at operating temperatures in these power devices, with application of low current bias. The mechanisms governing the expansion and contraction of these stacking faults is complex. In this work, we have utilized a recently developed [4], non-destructive ultra-violet photoluminescence (UVPL) mapping technique to investigate the expansion/contraction of SSFs from individual BPDs instead of clusters of BPDs. For this we used 20 um thick, 4H-SiC epilayers, grown on 4H SiC substrates, which were cut 8° off-axis towards the [11-20] direction The motion of SSFs was generated by stressing the faulted regions under variable UV laser intensities. The UVPL measurements were carried using an argon ion UV laser, with principle UV excitation lines at 364 nm and 351 nm and images were collected in the 600 to 1000 nm range. Focusing lenses were used to vary the laser light intensity at the imaged regions. A sequence of images from the faulted region under UV exposure was obtained using a computed controlled, liquid nitrogen cooled CCD detector mounted on the probe station. All the measurements were done at room temperature. Using this technique, we were able to obtain real time, in-situ images to investigate changes in SSFs and their bounding partials originating from individual BPDs. The timed sequence of exposures were started under high laser power intensity (~1-2 x10^{-3} W/μm^2) in order to expand the SSFs and observe motion of the bounding partials. Following this, a next set of UV exposures at lower power (~1-2 x10^{-5} W/μm^2) was performed. The images observed, for the first time, show the contraction of individual SSFs and a reverse motion of the bounding partials. The motion of SSFs and the bounding partials during expansion and contraction of the SSFs are found to be different and will be discussed in the presentation. [1] J. P. Bergman, et. Al, Mater. Sci. Forum 353-3 (2000) 299; [2] R. E. Stahlbush, et. Al, Mater. Sci. Forum 389 (2002) 427; [3] J. D. Caldwell, et. Al, Appl. Phys. Lett. 90 (2007) 143519; [4] R. E. Stahlbush, et. Al, Mater. Sci. Forum 556-557 (2007) 295.

10:00 AM Break

10:20 AM

O6, Influence of Stacking Fault Generation and Half Loop Array on Electrical Behavior of 4H-SiC 10 kV PiN Diodes: *Qingchun (Jon) Zhang*[1]; Anant Agarwal[1]; Robert Stahlbush[2]; Charles Scozzie[3]; Albert Burk[1]; Michael OLoughlin[1]; [1]CREE; [2]Naval Research Laboratory; [3]Army Research Laboratory

The influence of stacking fault (SF) generation on the reverse blocking and reverse recovery characteristics has been investigated on SiC 10 kV, 1 A PiN diodes. For the first time, we have observed that the generation of SFs under forward biased stress increases the reverse leakage current, and reduces the stored charges. The SiC PiN diode was made on a 125 μm-thick SiC drift layer with Nd = 5-6×10^{14} cm^{-3}. Aluminum ion-implantation was used to form the P$^+$N junctions. Multiple-zone JTE was implanted by Boron around the device periphery. The PiN diodes with different BPD densities and half loop array (HLA) density were selected and stressed with 1 A DC (~30 A/cm^2) flowing such that the implanted P$^+$N junction was forward biased. The forward and reverse I-V characteristics and reverse recovery performance were measured before and after electrical stress. The diode made on a high BPD density material has shown a significant forward voltage drop increase after electrical stress as shown previously. More significantly, the reverse leakage current was dramatically increased and the breakdown voltage was decreased. A reduced stored charge after stress was observed from reverse recovery tests before and after stress with the same forward current, which indicates a carrier lifetime reduction. On the contrary, the PiN diode made on BPD-free material didn't show any degradation in all electrical characteristics. The effect of the presence of half loop arrays will also be investigated. More data and detailed analysis will be presented in the full paper. This research was funded through the Cooperative Agreement W911NF-04-2-0022 program supported by the Army Research Laboratory in Adelphi, Md.

10:40 AM

O7, Reducing Basal Plane Dislocation Density in Nitrogen and Aluminum Doped 4H-SiC Epilayers: *Virginia Wheeler*[1]; Brenda VanMil[1]; Rachael Myers-Ward[1]; Charles Eddy[1]; Robert Stahlbush[1]; Nadeemullah Mahadik[1]; D. Kurt Gaskill[1]; [1]Naval Research Laboratory

Silicon carbide (SiC) is a promising material for high-temperature, high-voltage, and high-power switching applications. However, extended defects propagating from the substrate into the epitaxially grown active regions of these bipolar devices still limit device reliability and performance. Basal plane dislocations (BPDs) are of particular concern since they act as nucleation sites for Shockley-type stacking faults, which can cause degradation in minority carrier lifetimes and forward voltage drifts [1]. Several methods have been investigated to reduce the BPD density in epilayers on 8° off-cut wafers including KOH etching prior to growth [2,3], varying growth parameters [4], and *ex-situ* or *in-situ* growth interrupts [5,6]. Previous studies showed that *in-situ* growth interrupts notably enhance the BPD to TED conversion in low-doped n-type SiC layers, but for power devices it is critical to have BPD mitigation in the n$^+$ buffer layer to prevent any deleterious effects from SF formation in forward bias operation. This work investigates the effect of nitrogen and aluminum doping on the BPD to TED conversion efficiency. Epitaxial layers were grown in an Aixtron/Epigress VP508 horizontal hot-wall reactor on n$^+$ 4H-SiC substrates off-cut 8° toward the <11-20> direction. All films investigated were deposited using a standard silane (2% SiH$_4$ in H$_2$) and propane (C$_3$H$_8$) chemistry at 1580°C and 100 mbar pressure. Previous studies showed that a high BPD conversion efficiency could be obtained using an *in-situ* 45 min. growth interrupt at 1580°C with 10 sccm of propane [6]. For this work, the optimized growth interrupt was employed in a series of unintentionally doped (UID) and intentionally doped (ID) films. Intentional doping was achieved using a nitrogen and trimethylaluminum sources for n-type and p-type films respectively. Ultraviolet photoluminescence (UVPL) imaging was utilized to identify the BPDs extending into and through the grown epilayers. Atomic force microscopy and Nomarski microscopy was used to evaluate the surface roughness and film morphology. The effectiveness of an *in-situ* growth interrupt was found to be dependent on

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nitrogen doping concentration. Conversion efficiency profiles show an abrupt increase in BPD conversion at the growth interrupt for low-doped nitrogen films ($<10^{16}$cm^{-3}), while epilayers with high nitrogen concentrations show minimal BPD conversion at the interrupt and overall. The effect of growth rate and film thickness on BPD conversion efficiency in highly doped nitrogen layers will also be presented. For UID p-type films (hole concentrations $<5\times10^{15}$ cm^{-3}), BPD conversion took place throughout the epilayer. This phenomenon is similar to that observed in 4° material [7], but the conversion rate is much slower in the 8° material. ID aluminum films exhibited less total BPD conversion, suggesting that Al not responsible for spontaneous conversion in UID films. SIMS data will be presented for comparison.

11:00 AM

O8, Improved Surface Morphology of 4H-SiC Homoepitaxial Layers Grown on Si-Face 4° off-Axis Substrates: *Swapna Sunkari*[1]; Timothy Oldham[1]; Janna Casady[1]; Jeffrey Casady[1]; [1]SemiSouth Laboratories, Inc.

Homoepitaxial growth on 4H-SiC substrates is a key technology to fabricate unipolar and bipolar devices. Smooth surface morphology free of macroscopic step-bunching and fewer defects in the epilayers is recognized as one of the key issues for improving device performance. The quality of the epitaxial layers grown mainly depends on the process conditions and to some extent on the underlying substrate and its off-axis orientation. Optimized process conditions can highlight or suppress the crystalline imperfections as certain morphological defects on the epilayer, which can significantly influence the electrical characteristics of the devices fabricated. Epitaxial layers were grown at temperatures between 1550 -1650 ºC and pressures between 75 and 150 torr. Nomarski optical microscope and an Optical Surface Analyzer (OSA) inspection system were used to count and analyze defects both on substrates and epitaxial layers. In our previous work, we demonstrated that good quality epilayers with relatively smooth surface morphology and fewer defects can be grown on 4° off-axis substrates [1]. In this study, we present our recent process development efforts of growing epilayers free from step-bunching and very few growth related epi-defects. We optimized the process conditions by varying the C/Si ratio and process pressure keeping the growth temperature and SiH$_4$ flow rate fixed to our standard process. The C/Si ratio was varied in a limited range from 1.2 to 2.0 by changing only carbon precursor flow rate. After preliminary results it was noted that the step-bunching became more pronounced with increasing thickness of the epilayers [2, 3]. A 6µm thick epilayer had a smooth surface morphology with no step-bunching; whereas the step-bunching became noticeable when a 15µm thick epilayer was grown under same conditions. Our standard 4° process reproducibly produces an intra wafer thickness uniformity of 2%, with a growth rate of 5 µm/hr, doping uniformity of 6%, surface roughness Ra 1.93 nm, and total defect densities around 3.2 cm^{-2}. The new process resulted in repeated intra wafer thickness uniformity of 3%, with an increased growth rate of 6.3 µm/hr, and doping uniformity of 8%. Much smoother surface Ra 1.1 nm has been achieved with a reduced total defect densities around 1.8 cm^{-2}, which includes substrate defect densities around 0.75 cm^{-2}. Also these optimized conditions resulted in a much cleaner process therefore reducing the maintenance cycle time. The low defect density and improved surface morphology of epitaxial layers resulted in the production of 10A schottky diodes with a good yield of 72%. Further process improvement with varying temperature and ramp-up conditions is underway to achieve reduced defect densities and a smoother surface.

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O9, High-Purity Semi-Insulating 4H-SiC Homoepitaxy at a High Growth Rate Using Dichlorosilane for High Power Devices: *Iftekhar Chowdhury*[1]; MVS Chandrashekhar[1]; Pawel Kaminski[2]; Roman Kozlowski[2]; Paul Klein[3]; Joshua Caldwell[3]; Kurt Gaskill[3]; Tangali Sudarshan[1]; [1]University of South Carolina; [2]Institute of Electronic Materials Technology; [3]Naval Research Laboratory

High voltage SiC devices (~10kV) are of great interest in recent years for smartgrid and other power conversion applications. Recent demonstrations include PiN diodes, Schottky barrier diodes, DMOSFET and implanted VJFET. Epitaxial layers ~100 µm are required to obtain a breakdown voltage ~10 kV. To obtain such large thickness with standard epitaxy processes ~6-7µm/hr, a process time of more than 10 hours is required with the consequent high cost. A new process that overcomes this limitation by adding HCL or using halide precursors has been developed recently. However, the growth of thick epitaxial layers (>50µm) with low doping concentration (<1E14 cm^{-3}) remains a very difficult task, since the surface morphology usually degrades, exhibiting various morphological defects. In this paper, we will present results on high quality, thick 4H-SiC (0001) 8^0 off-axis toward (11-20) that have been grown in a vertical hot-wall chemical vapor deposition (CVD) furnace (temperature 1500^0-1700^{0}C, pressure 80-300 torr) at a high growth rate using a novel precursor Dichlorosilane, a kinetically favorable halide precursor. RMS roughness in the range of 0.3-0.4 nm with no morphological defects (carrots, triangular defects etc.) has been shown at growth rates 30-100 µm/hr, 5-16 times higher than the conventional speed. The surfaces were specular. Microwave photoconductive decay (µPCD) measurement showed high injection lifetime in the range of 2µs. Site-competition epitaxy was clearly observed over a wide C/Si ratio window (0.9-1.7), with doping concentration <1E14 cm^{-3}. By maintaining a highly pure growth environment and adjusting the C/Si ratio, we have systematically produced thick high purity semi-insulating (HPSI) epilayers over a C/Si ratio window of 1.3-1.5, a regime we call defect-competition epitaxy. The full width at half maximum (FWHM) obtained using x-ray rocking curves was as narrow as 8arcsec, which indicates the high quality of the epilayers. Micro-Raman spectroscopy showed the 4H polytype uniformity of these HPSI-layers. Resistivity of 1.5×10^9 Ohm-cm was determined using transmission line model (TLM) method. Comparison of secondary ion mass spectra (SIMS) between a low doped n- epilayer grown at lower C/Si ratio (~0.9) and a HPSI-epilayer grown at higher C/Si ratio (~1.4) showed no differences in terms of N, Al and B residual impurity concentrations. A correlation of impurity concentration with measured resistivity implied a compensating trap concentration of ~10^{15} cm^{-3} present in the HPSI-epilayer. High resolution photo induced transient spectroscopy (HRPITS) analysis identified these traps as Si-vacancy related deep defect centers, with no detectable EH6/7 and Z$_{1/2}$ levels, consistent with the higher C/Si ratio.

11:40 AM

O10, Vanadium Doping Using VCl$_4$ Source during the Chloro-Carbon Epitaxial Growth of 4H-SiC: Bharat Krishnan[1]; Siva Kotamraju[1]; *Yaroslav Koshka*[1]; [1]Mississippi State University

Bulk growth of semi-insulating (SI) SiC has been extensively investigated, and various growth techniques for producing SI SiC wafers have been commercialized. However, relatively few reports are available on epitaxial growth of SI SiC. In this work, we report the first data on using VCl$_4$ as a vanadium source during the chloro-carbon epitaxial growth of 4H-SiC. The previously developed chloro-carbon epitaxial growth technique based on using chloromethane (CH$_3$Cl) as the carbon precursor was used. SiCl$_4$ was used as the silicon precursor. In situ vanadium doping was carried by H$_2$ bubbling of vanadium tetrachloride (VCl$_4$). While the low-temperature chloro-carbon epitaxial growth has been traditionally conducted at 1300°C in our previous work, the early vanadium-doping experiments in this work utilized a higher growth temperature of 1450°C. In addition, experiments at 1600°C were also conducted to achieve thick epitaxial layers better suitable for comprehensive materials characterization. Steep dependence of V concentration (measured by SIMS) on VCl$_4$ flow rate (controlled by changing the H$_2$ flow rate through the bubbler at a fixed bubbler temperature) was observed. It appears that the steepness of the dependence increased when approaching the limit of the V concentration before morphology degradation. Featureless epilayer surface was observed by SEM in the epitaxial layers grown at 1450°C with VCl$_4$ flow rates of up to ~0.0013-0.0014 sccm (corresponding to [V] = 4-6x10^{16} cm^{-3}). At higher VCl$_4$ flows, triangular-shaped defects formed, and their concentration increased with the vanadium supply. Electrical activation of the incorporated vanadium was confirmed by the increase in the intensity of the V-related infrared photoluminescence (PL) by almost an order of magnitude in the epitaxial layer doped to [V] = 4x10^{16} cm^{-3} as compared to an undoped reference epitaxial layer. Electrical measurements in lower-doped samples showed the values of the net donor concentration consistent with a partial compensation of nitrogen donors with vanadium acceptors. At higher V flow, full compensation and semi-

insulating behavior was observed. In a 50 µm-thick sample grown at 1600°C, non-contact capacitance based resistivity measurements revealed the values of resistivity in the range of 2-4x10^{5} Ohms-cm. Thick epitaxial layers grown at 1600°C, with the growth rate in the range from 60 to 90 µm/hr, were used to evaluate the effect of V doping on the crystalline quality. While a defect-free epilayer surface morphology was observed in thick epitaxial layers exhibiting semi-insulating behavior, the X-ray rocking curves showed significant broadening. The FWHM increased from around 14 arcsec in the reference (undoped) sample to as high at 60 arcsec in the vanadium doped sample. Detailed investigation of the morphology degradation versus V flow during the growth at 1450°C and 1600°C will be presented.

Session P: One-Dimensional Photovoltaics

Thursday AM   Room: 131
June 24, 2010   Location: University of Notre Dame

Session Chairs: Joan Redwing, Pennsylvania State University; Mike Scarpulla, University of Utah

8:20 AM

P1, Fabrication of Individual Silicon Nanowire Radial Junction Solar Cells: *Chito Kendrick*[1]; S Eichfeld[1]; Y Ke[1]; X Weng[2]; J Redwing[1]; X Wang[3]; T Mayer[3]; [1]Department of Materials Science and Engineering, Penn State University; [2]Materials Research Institute, Penn State University; [3]Department of Electrical Engineering, Penn State University

Radial p-n silicon nanowire (SiNW) solar cells are of interest as a potential pathway to increase the efficiency of crystalline silicon photovoltaics by reducing the junction length and surface reflectivity. Our studies have focused on the use of vapor-liquid-solid (VLS) growth technique to produce p-type silicon nanowires to act as the collection core of the solar cell. For the n-type shell layer, both low pressure chemical vapor deposition (LPCVD) and thermal diffusion of phosphorus have been investigated. The effect of process parameters and junction formation technique were investigated using single wire measurements which provides information on the diode characteristics and solar cell properties. High aspect ratio p-type SiNW arrays (300 - 500 nm diameter) were initially grown on both patterned and unpatterned gold-coated (111) Si substrates by CVD using $SiCl_4$ as the source gas and B_2H_6 as the p-type dopant source. Four point resistance measurements on individual p-type silicon nanowires indicated a nanowire resistivity of 0.01 O-cm for a $SiCl_4$:B_2H_6 ratio of 1x10^{-4}. Prior to the junction fabrication, the gold tips were removed from the wires using Transene gold etchant for 40 minutes at a solution temperature of 40°C. Additional cleaning was done by thermally oxidizing the wires for 2 hours to produce a 150 nm thick SiO_2 layer, which was later removed before the n-type shell fabrication. The oxidation process also thins the wires to diameters that are needed for electrical measurements. The epitaxial re-growth of n-type Si shell layers on the Si nanowires was then investigated using SiH_4 as the source gas and PH_3 as the dopant. Highly conformal coatings were achieved on nanowires up to 25 µm in length. The microstructure of the Si shell layer changed from polycrystalline to single crystal as the deposition temperature was raised from 650°C to 950°C. For the thermal diffusion of the n-type shell, an annealing temperature of 1000°C was applied for 13 minutes with the introduction of $POCl_3$ dopant gas.Electrical test structures were fabricated by aligning released SiNWs onto pre-patterned substrates via field-assisted assembly followed by selective KOH etching to remove part of the n-type shell layer before contact deposition. Preliminary current-voltage measurements of the radial p-n SiNWs diodes fabricated with re-grown Si shell layers demonstrate rectifying behavior with an ideality factor of 1.67 and low reverse leakage current.

8:40 AM

P2, Wire Textured Multicrystalline Silicon Solar Cells: *Kejia Wang*[1]; Oki Gunawan[1]; Naim Moumen[1]; George Tulevski[1]; Hisham Mohamed[2]; Babak Fallah[3]; Emanuel Tutuc[3]; Supratik Guha[1]; [1]IBM T.J. Watson Research Center; [2]Egypt-IBM Nanotechnology Research Center Labs; [3]University of Texas Austin

Currently the multicrystalline (MC) Silicon is an important material for solar cell market because of its low cost and easy assembly into modules. One of the main challenges for MC Si solar cells is that there is no satisfactory and easy process for texturing MC Si surface to reduce reflectance. For single crystal Si, the commonly use method to texture surface is KOH based solution etching. However, this process cannot be used for MC Si due to the anisotropic nature of KOH etching. In this work, we have investigated enhanced light trapping in MC Si solar cell using wire array texturing. MC Si surface was first functionalized using aminopropyltriethoxysilane (amino-silane). Then one monolayer carboxyl polystyrene microspheres was patterned onto Si surface as shown in Figure 1. This process requires no spinning based steps and easy to scale up to larger wafer sizes. Then, using this monolayer microsphere as the etching mask, wires were etched using reactive ion etching to texture the MC Si surface (Figure 2). The measured reflectivity spectra in Figure 3 showed that there was a significant drop in the reflectivity for the wire textured MC Si devices. The weighted average reflectivity (WAR) respect to solar spectrum AM1.5 was used to evaluate the reflectance. Before wire texturing, the WAR for MC Si is ~ 22.6%. After the wire texturing, the WAR drops to 13.5%. Compared with standard KOH textured single crystal Si, which has a WAR of 11.9%, this wire texturing provide an efficient way to reduce the surface reflectance of MC Si. Solar cell devices were then fabricated based on the wire textured MC Si. The wire textured device performance and the control planar MC Si device were measured and plotted in Figure 4. The wire textured devices display 20% higher short circuit current densities, which is due to the enhanced light trappings. The efficiency of the wire textured MC Si solar cell is ~ 7.5%, which is also same as the planar MC Si solar cell. The device performance of wire textured MC Si solar cell is limited by the higher series resistance (6-9O), compared to 2.6 O of a planar control sample. Using a Jsc-Voc measurement we can exclude this series resistance effect, we observe 7~16% enhancement in pseudo-efficiencies for wire textured MC Si solar cells.

9:00 AM

P3, Efficiency Enhancements for Copper Contaminated Radial p-n Junctions over Planar p-n Junctions in Silicon: Akram Boukai[1]; *Alec Talin*[2]; Gregg Gallatin[2]; Aaron Katzenmeyer[3]; Peidong Yang[4]; [1]University of Michigan; [2]NIST; [3]Sandia National Laboratories; [4]UC Berkeley

The need to employ high purity, semiconductor grade Si in the fabrication of Si solar cell significantly increases the cost of Si based photovoltaics. Reducing this cost by employing cheaper, metallurgical grade Si would also substantially degrade cell performance due to the diminished carrier diffusion length. Radial pn junction solar cells based on vertical arrays of Si nanowires have been proposed as a possible route to circumvent the requirement for high purity material by orthogonalizing the direction of light absorption and minority carrier diffusion necessary to reach the junction. Here we present first experimental results on radial pn junction arrays fabricated by a combination of optical lithography and deep reactive ion etching deep vias in boron doped Si wafers followed by pn junction formation using a spin-on glass phosphorus source. To simulate the effects of impurities in metallurgical grade Si, we intentionally contaminate our devices by depositing Cu films on the back side followed by thermal annealing. Cu contamination decreases the electron diffusion length from ~500 µm for clean Si to ~0.3 µm for the contaminated Si, as measured using electron beam induced current technique. We test our devices under simulated 1 sun conditions and report that while planar Si pn junction has superior performance for clean semiconductor grade Si, the radial arrays outperform the planar junction formed with Cu contaminated Si. Furthermore, we demonstrate that radial junctions with a 4 µm pitch perform better than those with a 10 µm pitch, and that the device performance is consistent with a simple model based on solution of the Poisson and carrier diffusion equations for the radial geometry pn junctions.

9:20 AM Student

P4, Wafer Scale Si Nanowire Arrays for Photovoltaic Applications: *Yi Jing*[1]; Ke Sun[1]; Deli Wang[1]; [1]University of California, San Diego

Photovoltaic devices are attractive candidates for clean and renewable energy sources. Although the majority of the commercial solar cells are based on Si thin film devices, vertical aligned Si nanowire array is a promising alternative for low cost and high efficiency photovoltaic devices because of enhanced light absorption and improved carrier separation/collection. In this research, large area coaxial Si p-n junction nanowire solar cells were fabricated and characterized. Instead of conventional VLS growth, a HF based aqueous solution method was employed to etch vertical aligned Si nanowire array with desired doping and crystalline orientation. Without size limitation, multiples Si wafers can be etched together to produce nanowire arrays, which greatly reduces the cost. The length of the nanowires can be easily controlled by tuning the etching time. In this report, test grade 2-inch n-type (100) Si wafers were used. After solvents cleaning, Si wafers were immersed into an aqueous solution of HF and silver nitrate with a concentration of 5M and 0.02M respectively for 11 minutes at 50°C, resulting in ~2µm long vertical aligned nanowire arrays on wafer surfaces. The produced silver film on top of nanowires was removed using nitric acid. The coaxial p-n junction was formed by boron diffusion into the etched Si nanowires. Transparent indium tin oxide (ITO) was sputtered onto the surface of the nanowires as front contact and indium back electrode was formed using soldering iron. The nanowire devices were characterized under dark and with AM1.5 solar simulator illumination: an open-circuit voltage of 0.51V and a short-circuit current density of 40.5mA/cm^2 were obtained. The devices showed an energy conversion efficiency of 3.0% and fill factor of 0.25. Further improvement of front and back contacts are investigated to enhance the efficiency. This research will lead to a low cost fabrication process, mass manufacturable, high effieciency Si nanowires p-n junction solar cells.

9:40 AM
P5, Late News

10:00 AM Break

10:20 AM Student

P6, Branched ZnO/Si Nanowire Heterostructure Based Photoelectrochemical Cell for Efficient Water Splitting: *Ke Sun*[1]; Banu Khaleda[1]; Yi Jing[1]; Namsoek Park[1]; Deli Wang[1]; [1]University of California, San Diego

Design and synthesis of nanoscale heterostructures has attracted significant attentions in recent years because of their unique properties, diverse functionalities, and potential applications in photovoltaics and photocatalytics [1]. Various nanowire-based heterostructures, such as axial, radial/core-shell, and branched structure, have been developed and studied, due to their prominent tunable functionalities and greatly enhanced surface reactivity. These types of structure have helped scientists in hydrogen generation from water splitting. In principle, nanoheterostructure is working as a photoelectrochemical (PEC) anode/cathode generating electron/hole pairs from incident photons and then generated electrons reduce hydrogen ions. In this work, we report our research effort on developing efficient PEC cells for water splitting based on a branched n-ZnO/p-Si nanowire heterostructure from a cost-efficient and robust solution-phase integration process. Wafer-scale and highly dense vertical arrays of Si nanowire arrays were prepared using metal-assisted electroless etching [2]. SEM and TEM investigations show the vertical alignment, smooth surface of etched Si nanowires and large variations in diameter (average around 70nm). ZnO nanowires, intrinsically n-type, were then synthesized on the ZnO seeded Si nanowire arrays using hydrothermal method. SEM studies show the growth of ZnO nanowires in between Si nanowires to form branched heterostructures with average diameter of 50nm and average length of 250nm. The ZnO/Si n/p heteorstructures is then immersed in neutral electrolytes (pH=7) due to the less stability of ZnO in acidic or basic solution [3] and the photoelectrochemical production of hydrogen were tested under solar illustration (AM 1.5G) and the overall hydrogen production efficiency of the PEC cell is evaluated. The branched nanowire configuration enables low cost direct integration of heterogenerous nanomaterials with reduced defect density for high efficiency hydrogen generation.

10:40 AM

P7, Solar Cells Based on ZnO/ZnS Core-Shell Nanowires Arrays: *Aurelien Du Pasquier*[1]; Shamgzhu Sun[2]; Elan Coleman[2]; Bruce Willner[2]; Gary Tompa[2]; [1]Rutgers State University; [2]SMI, Inc.

ZnO nanorod arrays have been proposed for their application in photovoltaic devices, owing to the ease of growing arrays of high crystalline quality, low cost and low toxicity of ZnO, and well controlled length and shape nanowires. Since ZnO is an n-type semiconductor with a wide bandgap of 3.3 eV, visible light absorption must be provided by an associated p-type semiconductor. In particular, extremely thin absorber (ETA) solar cells could greatly benefit from this nanostructure, because light absorption would occur parallel to the length of the nanorods, but charge separation can occur normal to the nanorods, with increased efficiency. Hybrid photovoltaic devices have been demonstrated using poly (3-hexylthiophene) (P3HT) as light absorber and hole transport phase [1], and band alignment with ZnO can be achieved with Mg doping of ZnO [2]. Another approach is to design n-core/p-shell structures using a core of ZnO nanowires and a shell of ZnS. Bandgap control is achieved through the staggered type II heterojunction, where the effective bandgap at the junction can be calculated as the difference between the valence band level of ZnS, and the conduction band level of ZnO [3]. ZnO/ZnS core-shell nanorods have been prepared from solution grown ZnO nanorods [4]. ZnO/ZnTe core-shell nanorods have also been prepared by chemical vapor deposition [5]. Here, we will present initial MOCVD growth results of ZnO-ZnS core-shell nanostructures characterized via SEM, XRD and UV-vis spectroscopy. Their efficiency in photovoltaic devices of the type FTO/ZnO-ZnS/Au and FTO/ZnO-ZnS/P3HT/Au will be reported by external quantum efficiency and I-V measurements under simulated sunlight. References: Olson, DC Lee, YJ White, MS Kopidakis, N Shaheen, SE Ginley, DS Voigt, JA Hsu,,J.W.P. Journal of Physical Chemistry C 111, 16640-16645 (2007); J. Piris, N. Kopidakis, DC Olson, SE Shaheen, DS Ginley, and G Rumbles, Adv. Funct. Mater. 17, 3849–3857 (2007); J. Schrier, DO Demchenko, L-W Wang and AP Alivisatos, Nanolett. 7, 2377 (2007); JJ Uhlrich, R Franking, RJ Hamers, and TF Kuech, J. Phys. Chem. C 2009, 113, 21147–21154 21147; HY Chao, JH Cheng, JY Lu, YH Chang, CL Cheng, YF Chen, Superlattices and Microstructures 47, 160-164 (2010).

11:00 AM Student

P8, Fabrication of Subwavelength Pillar Arrays on GaAs by Confined Self-Assembly Technique for Broadband Antireflection Coating: *Dae-Seon Kim*[1]; Min-Su Park[1]; Yon-Kil Jeong[1]; Wu Lu[1]; Jae-Hyung Jang[1]; [1]Gwangju Institute of Science and Technology

Multilayer thin films are widely used for antireflection coatings of various devices such as solar cells, photodetectors, and optical amplifiers to minimize the optical loss due to surface reflections. Although thin film coatings are ideal for antireflection coatings in narrow band applications, subwavelength structures (SWS) are preferred for broad band applications. So far SWS have been fabricated by nanolithographic techniques such as electron beam lithography, nanoimprint lithography and holographic lithography. Even though these methods have successfully demonstrated SWS with good optical properties, low cost process technologies are highly needed for manufacturing of optical devices requiring broadband antireflection coating. In this study, SWS on GaAs substrates were fabricated by using the confined convective self-assembly1 method followed by inductively coupled plasma reactive ion etching (ICP-RIE). This method provides a much simpler and cheaper process and opens the possibility of large area SWS fabrication at low cost. Monolayer consisting of 300-nm-diameter polystyrene spheres were prepared on GaAs substrate using the confined convective self-assembly method. Either multilayer or monolayer polystyrene spheres could be assembled on the substrate by controlling the lift-up rate and the substrate temperature. The closely packed monolayer was subsequently treated by O2 reactive ion etching (RIE) process (30 mTorr chamber pressure, 30 SCCM O2). After the exposure to O2 plasma for 60 sec, the diameter of polystyrene spheres decreased from 300 nm down to 250 nm. The resulting 250-nm-diameter sphere arrays with 300-nm-pitch were used as the etching mask for the pattern transfer by ICP-RIE. Subwavelength structures consisting of pillar arrays with aspect ratios of 0.4, 1.35 and 3.63 were fabricated by controlling the etching time of ICP-RIE (7.5 SCCM SiCl4, 60 SCCM Ar). Finally the

remnant polystyrene spheres were removed by O2 RIE process. The reflectance of the fabricated SWS was measured at wavelength ranging from 300 to 1000 nm under the normal incidence. Reflectance of the bare GaAs substrate was higher than 30% throughout the wavelength range investigated in this study. For comparison, the GaAs substrates coated with single layer SiNX exhibited very low reflectance of 1% at the wavelength between 550 and 700 nm. The GaAs with SWS in this work exhibited reflectance lower than 8.5% throughout the wavelength range investigated. The low reflectance achieved by GaAs textured by the nano-pillar SWS is attributed to the nature of subwavelength structures which cannot be resolved by the incident light. Continuous transition of the effective refractive index from the top surface to the substrate dramatically reduces the surface reflection by minimizing the refractive index mismatch at the interface2. The fabrication details and the optical measurement results of the SWS with various aspect ratio and various fill factors will also be discussed.

11:20 AM Student
P9, Hybrid Solar Cell Based on Patterned Nanopillar/P3HT Heterojunction:
Giacomo Mariani[1]; [1]University of California, Los Angeles

In this work, we present a hybrid solar cell design that combines together catalyst-free patterned GaAs nanopillar with P3HT polymer, mainly used in organic and plastic solar cell. Hybrid solar cells integrate conjugated polymers, responsible for high processability at low cost and high optical absorption coefficient, and semiconducting nanostructures, responsible for high mobility required in carrier extraction. We have investigated a hybrid photovoltaic cell realized by n-doped GaAs patterned nanopillars and P3HT (semiconducting polymer) that acts as a hole transport layer. Patterned nanopillars grown by MOCVD were exploited thanks to their catalyst-free growth mode that eliminates any catalyst (i.e. Au) diffusion into the nanopillars that could hinder the electron-hole pair extraction, such a paramount process in solar cells. Our inherently lattice-matched growth capability also avoids threading dislocations that normally act as recombination centers, worsening the leakage current in pn-junction based devices. Furthermore, surface state density in nanopillars is a major-concern problem that reduces the effective conductivity of the nanostructure due to a depletion region that creates near the interface. Many efforts have been carried out to quench this effect by passivating the nanostructures prior to device fabrication. Comparisons were made in terms of photocurrent density-voltage (J-V) characteristics and external quantum efficiency (EQE), standard figures of merit in the photovoltaic field. Passivated PV devices are measured along with un-passivated solar cells and control cell. The best un-passivated PV device exhibits an open circuit voltage (VOC) of 0.2V, short circuit current density (JSC) of 8.7 mA/cm2 and a fill factor (FF) of 32% whereas passivation showed a drastic change in terms of device performance. The best passivated PV device delivers a VOC=0.18V, JSC=8.6 mA/cm2 and a fill factor FF above 42%. All measurements are carried out under 1-sun AM 1.5 direct illumination at room temperature. Extremely low leakage currents in reverse-biased mode (ILEAKAGE<10nA) are detected. This can be attributed to a high-quality crystalline growth in the nanopillars. EQE characteristics for the passivated samples show a quantum efficiency above 50% between 650nm and 850nm, revealing a relative increase of ~10% with respect to the case without any passivation. With respect to previous work on catalysed growth, the power conversion efficiency went from η=1.04% (un-passivated device) to η=1.44% (passivated device). This work demonstrates the high dependency of hybrid nanostructured PV device performance in terms of exciton dissociation/transport/extraction when the nanopillars are chemically treated before processing. Also, the interpenetrating polymer/semiconductor network shows an outstanding current density whereas the open circuit voltage can be furtherly improved by a better work function alignment between P3HT and GaAs.

11:40 AM
P10, Dissociation of Photo-Generated Excitons on Carbon Nanotubes at Type-II Heterojunctions: *Dominick Bindl*[1]; Michael Arnold[1]; [1]UW Madison

Semiconducting single walled carbon nanotubes (s-SWCNTs) are attractive as absorbing materials in photovoltaic devices. S-SWCNTs have large absorption coefficients, (> 10^5 cm^{-1}) with optical bandgaps from 1.0 – 1.3 eV. In addition, s-SWCNTs have excellent charge transport properties, are solution processable,

and offer enhanced photo-oxidative stability relative to photovoltaic polymers. Despite their promise, s-SWCNT have had limited impact in photovoltaics. A primary reason for this is the challenge associated with overcoming the large exciton binding energy (0.2 – 0.5eV) of photogenerated charge carriers in SWCNTs. In organic photovoltaics, exciton dissociation is achieved through a donor/acceptor type-II heterojunction in which the molecular orbital energy offset between the donor and acceptor is greater than the exciton binding energy. A similar strategy can be used to dissociate excitons in nanotubes; however, the energy levels of nanotubes are dependent on diameter, chiral angle, and local dielectric environment. For this reason, the selection of materials that form a type-II heterojunction with s-SWCNT is nontrivial. Here we experimentally evaluate donor/acceptor candidates for achieving exciton dissociation. We have utilized s-SWCNT/donor or acceptor/insulator/metal photoactive capacitors. In these capacitors, excitons are photogenerated in the nanotubes via near infrared (NIR) illumination at their E_{11} optical band gap transitions, and exciton dissociation is measured as a transient photocurrent and photovoltage response to modulated illumination. This technique is advantageous in that it does not utilize an externally applied bias and thus avoids misleading, photoconductive or heat-based changes in resistance and electrical current upon illumination even in the absence of exciton dissociation. Optical excitation in the NIR ensures that only the s-SWCNTs are excited rather than the donor or acceptor materials. We have characterized a variety of semiconducting polymers and small molecules as donors or acceptors to s-SWCNT using the photoactive capacitors. Dissociation of photogenerated excitons on s-SWCNT was observed at the interface of the nanotubes with fullerene-derivatives and poly(thiophene) derivatives such as P3HT and P3OT. In contrast to literature, no significant exciton dissociation was observed at interfaces with polymers such as MDMO-PPV or insulating polymers such as polycarbonate. PFO devices also failed to elicit a photoresponse. C60 interfaces resulted in the highest efficiency for exciton dissociation, a factor of three greater than C61-PCBM and all thiophene based devices - which were themselves an order of magnitude more responsive than PPV derived polymers. Our work demonstrates that s-SWCNT can serve as both electron donating and electron accepting materials in photovoltaic films. Through bias dependencies, it is concluded that exciton dissociation at the interface of fullerene/thiophene derivatives results in electron/hole transfer from s-SWCNT, respectively. Excitons photogenerated on C60, C61-PCBM, P3OT, P3HT and rr-P3HT in response to visible excitation were also dissociated at the interface.

Session Q: Oxide Thin Films

Thursday AM   Room: 138
June 24, 2010   Location: University of Notre Dame

Session Chairs: Bruce Hinds, University of Kentucky; Pat Lenahan, Pennsylvania State University

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8:20 AM
Q1, Pulsed-dc Reactive Sputtering Vanadium Oxide Thin Films for Microbolometers: *Bharadwaja Srowthi*[1]; C. Venkatasubramanyam[1]; N. Fieldhouse[1]; B. Gauntt[1]; O. Cabarcos[1]; Myung Yoon Lee[1]; S. Ashok[1]; E. C. Dickey[1]; T. N. Jackson[1]; M. Horn[1]; [1]Penn State University

Current industry requirements for microbolometers include fabrication of VO$_x$ thin films with high temperature coefficient of resistivity (TCR), low resistivity, low noise, good stability, and low temperature processing (<400 °C) for integration onto CMOS circuitry. In this work, VO$_x$ films were deposited using pulsed dc sputtering as an alternative to the usual industry-used process of ion beam sputtering. Reactive sputtering often exhibits sputter gas composition hysteresis due to reaction of the target with the sputtering gases. We will discuss the process control of VO$_x$ thin films grown in pulsed-dc reactive sputtering to tailor desired electrical properties. The process hysteresis in our pulsed dc sputtering was monitored using target current for various argon to oxygen ratios over a 5 - 100 mT pressure range. Film deposition rate, resistivity, and

temperature coefficient of resistance of the VO_x thin films deposited at various points on the sputtering gas composition curve also exhibited hysteretic behavior which could be tracked by the associated cathode current hysteresis. Structural characterization using X-ray diffraction, transmission electron microscopy (TEM), and Raman spectroscopy were utilized to correlate the film properties with the processing conditions. In particular, TEM analysis on the films processed with low processing pressures and oxygen partial pressures contained micro crystallites embedded in an amorphous VO_x matrix. These films also had film resistivity (0.1 to 1 ohm.cm) and TCR (-1.8 to -2.2% K^{-1}) in the range required for micro bolometer applications. Low temperature charge transport in vanadium oxide (VO_x) thin films was investigated to understand the correlation between the processing conditions and electrical properties. By using a combination of resistivity versus temperature measurements and simple theoretical arguments, it was identified that the temperature dependent resistivity, $\rho(T)$, of the VO_x thin films is dominated by a Efros-Shklovskii variable range hopping (ES-VRH) mechanism obeying the relation $\rho = \rho_o.\exp(T_o/T)^{0.5}$, where T_o is a measure of the degree of charge disorder of the VO_x films. Analysis in terms of charge hopping parameters in the low temperature regime was used to correlate film properties with the pulsed DC sputtering conditions. Finally, the 1/f noise of the VO_x films was measured and correlated with other film properties. The normalized power spectral density of pulse dc sputtered VO_x thin films was compared with ion beam sputtered films with comparable resistivity values ($\rho_{dc} = 0.43$ ohm.cm and 0.25 ohm.cm). The 1/f noise for samples deposited by the two techniques was similar. Assuming the carrier mobility is similar for films deposited by the two techniques this indicates that the Hooge parameter for pulsed dc sputtering and ion beam sputtered VO_x films is also similar. This suggests that the quality of pulsed dc sputtered VO_x thin films is comparable to industry quality ion beam deposited films.

8:40 AM Student

Q2, Defects in Low-κ Dielectrics and Etch Stop Layers for Use as Interlayer Dielectrics in ULSI: *Brad Bittel*[1]; P.M. Lenahan[1]; S. King[2]; [1]Penn State Univ.; [2]Intel Corp.

The electronic properties of low-κ dielectric thin films and etch stop layers (ESL) are important issues in present day ULSI development.1-6 The quality of low k dielectrics and there corresponding ESL is paramount to successful adoption of modern interlayer dielectrics (ILD). ESL are needed for ULSI processing and there is interest to find films with k values lower than the industry standard SiN with suitable properties. Leakage currents in general as well as reliability issues such as, time dependent dielectric breakdown (TDDM) and stress induced leakage currents (SILC) are critical problems that are not yet well understood in ILD. A topic of current interest is ultraviolet light (UV curing) of low-κ materials.5,6 We have made electron spin resonance (ESR) and current density versus voltage measurements on a moderately extensive set of dielectric/silicon structures involving materials of importance to low-κ interlayer systems. Most of the dielectrics studied involve various compositions of SiOC:H. In addition we have also made measurements on other dielectrics including SiO2, SiCN:H and SiN:H. In our study we have made ESR and current density versus voltage measurements both before and after exposing the dielectrics to UV light (hc/λ = 5 eV), and films that have experienced an industrial UV curing process. We observe extremely gross differences in the ESR spectra and leakage current versus voltage response of these low-κ films. We find that UV exposure consistently increases both the density of paramagnetic defects and the leakage current density at a given field. Paramagnetic point defects observed in these films include, E' centers, silicon dangling bond defects in which the silicon is back bonded to oxygen, possibly silicon and carbon dangling bond centers and likely organic radicals. Our preliminary results suggest the UV curing process creates paramagnetic centers which take part in trap assisted tunneling. This tunneling increases dielectric leakage current.   Our preliminary results indicate quite clearly that the processing parameters have extremely gross effects upon defect densities within these films. 1. F. Chen et al. Proc. of the Forty Third Int. Rel. Phys. Sym., 501 (2008); 2. Y. Ou et al., J. Electrochem Soc. 155, (12) G283 (2008); 3. J. Michelon and R. J. O.M. Hoofman, IEEE Trans on Dev. and Mcr. Rel. 6, 169 (2006); 4. C. Y. Kim, et al., Coatings Technology, 202, 5688 (2008); 5. S. Eslava, et al., J. Electrochem Soc. 155, G155 (2008); 6. E. Marhrez, et al., J. Applied Phys. 100, art. no.124106 (2006).

9:00 AM Student

Q3, Nanocluster and Nanocrystalline Si Trap Distributions within SiO_2/SiO_x/SiO_2 Field Oxides for Radiation-Tolerant Electronics: *Evan Katz*[1]; Zhichun Zhang[1]; Hap Hughes[2]; Kwun-Bum Chung[3]; Gerry Lucovsky[3]; Leonard Brillson[1]; [1]The Ohio State University; [2]Naval Research Laboratory; [3]North Carolina State University

We have used nanoscale depth-resolved cathodoluminescence spectroscopy (DRCLS) and spectroscopic ellipsometry (SE) to measure energies and spatial distributions of Si-related charge traps in SiO_2/SiO_x/SiO_2 field oxides for radiation-tolerant electronics. Suboxide layers within SiO_2/Si structures result in Si nanoclusters that reduce the flatband voltage shift by trapping ionized protons and electrons [1]. Such traps reduce the net positive charge during exposure to ionizing radiation that result in negative flatband voltage shifts and charge leakage pathways. We prepared SiO_2/SiO_x/SiO_2 gate dielectrics with reduced oxide concentrations and monitored their optical absorption and emission features with annealing and irradiation. These nanoscale structures segregate with annealing from amorphous Si into nanocrystalline Si surrounded by SiO_2 [2]. DRCLS and SE provide optical transitions at energies involving not only intra- but also interphase transitions due to their intimate contact and high area. Deconvolved DRCLS spectra distinguished spatially between traps associated with Si nanoclusters, Si nanocrystals, SiO_2 native defects, and Si ion implantation damage used to create Si-rich SiO_2. Understanding the physical nature of such traps may enable control of radiation-induced holes in higher-K dielectric SOI structures.To distinguish trap cathodoluminescence from implanted versus crystalline versus implant-damaged regions in the oxide stack, we varied incident beam energy E_B from 0.5 – 1 keV. The peak rates of electron-hole pair creation inside the SiO_2/SiO_x/SiO_2/Si(100) structure were separated by only ~3 nm. Higher E_B probe the SiO_x "bulk" and the lower SiO_x/SiO_2 regions. For a non-annealed but irradiated (7.6 Mrad(SiO_2)Co-60, 5.7 Mrad/hr) sample, we found defect levels located 3.5 and 3.9 eV below the conduction band of SiO_2. These traps increase with E_B until 0.8 kV, ~10 nm within SiO_x. The 2.00 and 2.55 eV (NBOHC and E' center) peaks increase with E_B and depth, probing deeper into SiO_2. Beyond 10-14 nm below the free surface, the intensity of the 3.5 and 3.9 eV defects decrease. Since the Si implantation occurred only within the outer 10 nm of SiO_x, we associate these defects with Si-nanoclusters and nc-Si grains. We also observed a 0.1 (0.05) eV defect shift to higher SE (DRCLS) energy with annealing. Both techniques are consistent with the energy levels of SiO_2 and Si for trap states at their interface located 0.3 eV above the valence band. Coupled with similar results for annealed and irradiated samples, these results demonstrate that: (i) the 3.9 and 3.5 eV defects located at Si nanoclusters and nanocrystals trap charge within narrow (10 nm) surface layers to improve radiation hardness, (ii) nanocrystals are more efficient traps than nanoclusters, (iii) ion implantation damage can not account for these traps, and (iv) these traps are most effective after annealing plus irradiation. These depth-resolved results validate the carrier trapping mechanism of SiO_x resistance to ionizing radiation.

9:20 AM Student

Q4, Nanoscale Depth-Resolved Electronic Properties of HfO_2/RPAN/Ge and HfSiON/RPAN/Ge Gate Dielectrics for Radiation-Tolerant Electronics: *Zhichun Zhang*[1]; E. J. Katz[1]; K.-B. Chung[2]; G. Lucovsky[2]; L. J. Brillson[1]; [1]Ohio State University; [2]North Carolina State University

We used nanoscale depth-resolved cathodoluminescence spectroscopy (DRCLS) to measure the energies and depth distributions of charge traps in HfO_2 and HfSiON high-k gate dielectrics on remote plasma-assisted nitrided (RPAN)/n-Ge for radiation-tolerant electronics. The drive for higher speed electronics has promoted development of high-k dielectrics to replace SiO_2 and substitution of higher mobility Ge for Si. The mechanisms by which electronically-active defects form in the Ge-dielectric gate stack under different process conditions as well as high energy irradiation are not yet understood. Defect control under these conditions can enable higher speed but also radiation-tolerant high-k dielectric/Ge MOSFET for space applications. Our previous work showed that rapid thermal anneal (RTA) in Ar at T>700°C eliminates the interfacial RPAN layer intended to reduce negative trapped charge for n-MOSFET under bias [1]. RTA also increases the nano-grain dimensions of the as-deposited nanocrystalline

HfO_2 films [1]. O-vacancies and interstitials clustered and pinned at the HfO_2 nanocrystalline grain boundaries trap electrons during exposure to ionizing radiation, leading to flatband voltage shifts and pathways for leakage current [2]. We used remote plasma-enhanced chemical vapor deposition (RPCVD) to deposit crystalline HfO_2 and amorphous HfSiON onto RPAN/n-Ge substrate at 300°C, then measured their optical absorption and emission spectra of samples versus annealing and irradiation. DRCLS provided the energy level transitions within the ultrathin gate dielectric layer and the dielectric-Ge interface, enabling defect identification in these nanoscale regions, their evolution with processing, and methods to control them. From the gate structure of the samples and Monte Carlo simulation of electron-hole pair generation versus incident electron beam energy E_B and excitation depth, $E_B=1$ keV probes mainly in the gate dielectric layer and the interface. DRCLS spectra show HfO_2-related defect emissions at 2.0, 2.7, 3.5, 4.0, and 4.5eV versus annealing and irradiation. These are assigned to different charge states of O-vacancies and interstitials, corresponding to X-ray absorption spectra (XAS) and spectroscopic ellipsometry (SE) transitions between defect states in the HfO_2 band gap. [2,3] RTA halves defect intensities by annealing out O-vacancies and interstitials and reducing grain-boundary surface area as nanocrystalline HfO_2 grain size increases[4]. However, ^{60}Co irradiation triples defect intensities in these annealed samples. Irradiation alters O-vacancy clustering and charge state in the larger nanocrystalline HfO_2 films, trapping electrons more efficiently in the oxide, potentially shifting flatband voltages. Compared to HfO_2, HfSiON suppresses Ge indiffusion with RTA and has much lower defect densities, particularly after irradiation. Nevertheless, RTA degrades radiation hardness for both HfO_2 and HfSiON. Hence HfSiON deposited on RPAN/n-Ge without RTA is the most radiation tolerant for MOS devices. These studies identify the defect levels in HfO_2 and HfSiON, reveal their radiation tolerance under different processing, and provide guidance for producing radiation-tolerant high-k dielectric/Ge MOSFETs.

9:40 AM Student

Q5, Nano-Gap Electrodes Formed at the Exposed Edge of $Au/Al_2O_3/Au$ Tunnel Structures Grown by Atomic Layer Deposition: *Bing Hu*[1]; Bruce J. Hinds[1]; [1]University of Kentucky

Fabrication of nanometer-scale electrode gaps is a critical step for numerous devices based on single molecule conduction as well as to serve as a probe for the fundamental transport properties of molecular materials such as organic conductors. Several techniques, such as mechanical break junction [1] and electromigration junction [2], have been developed to realize nano-gap electrodes but suffer from scaling and yield issues. Recently, a simple technique to fabricate the exposed edge of metal/Al_2O_3 (2.0 nm)/metal structure by photolithography-liftoff process for molecular electrodes was reported [3]. This technique uses highly controllable film thickness (Al_2O_3) to set the critical spacing between electrodes. After lift-off or etching process, molecules can bridge across the nm-thick insulator connecting top and bottom metal contacts. However, the system, with Ni metal contacts, possessed long term stability issues due to surface oxidation and hillock formation from stress release. Much of the molecular electronics literature to date has utilized Au-thiol chemistry to ensure clean inert surfaces for molecular contacts. However it is difficult to form stable Au-insulator tunnel junctions due to high surface energy and subsequent island growth of oxides on Au. To overcome these limitations, we used atomic layer deposition (ALD) to grow Al_2O_3 layer on Au electrodes that were modified with a self-assembled monolayer of alcohol groups. Reactive ion etching (RIE) was then used to expose the edge of the Au/insulator/Au structure for molecular electrode contacts. The $Au/Al_2O_3/SAM/Au$ tunnel junction, with a very thin insulator layer (1.6 nm), is stable and has a small tunneling current density about 0.01 A/cm2 at 0.1 V. This background tunnel current is two orders lower than that of metal/Al_2O_3 (2.0 nm)/metal structure by photolithography-liftoff process previously reported. In addition to molecular conduction studies, this electrode design has been employed to study photovoltaic organic materials. We have deposited a thin layer of Copper Phthalocyanine (CuPc) on the exposed edge of Au/Al_2O_3 (10 nm)/Au structure and observed large photocurrents that are over two orders higher than that of bulk CuPC material. The nano-scale gap between Au electrodes, which is controlled by the thickness of Al_2O_3, is smaller than the exciton diffusion length of CuPc thus allowing increased photocurrent. Schottcky barrier contact resistance was found to be the primary limiter of charge injection into the organic film. An electrode structure based on the exposed edge of $Au/Al_2O_3/Au$ tunnel junctions can provide a reliable method for the fabrication of molecular-scale devices and more efficient solar cells.

10:00 AM Break

10:20 AM Student

Q6, Surface-Interface Conductivity in Thin Film Gd-doped CeO_2: *Matthew Swanson*[1]; Lakshmi Krishna[1]; Natee Tangtrakarn[1]; Madhana Sunder[1]; P.D. Moran[1]; [1]Michigan Technological University

The ionic conductivity of a Gadolinium doped Ceria (GDC) interface/surface at temperatures between 300-700°C is of interest due to the application of the material as an electrolyte for low temperature Solid Oxide Fuel Cells (SOFCs). It has been asserted in the literature that the exceptionally high ionic conductivity observed in thin GDC films is due to the substrate/film interface or surface acting as a high conductivity path for ions [1, 2]. Those studies were not performed on single crystal GDC and, therefore, did not completely isolate the ionic conduction along the film surface and substrate/film interface. A study to extract the surface and interface contributions to the total ionic conductivity of GDC films has not been reported. This work addresses the need for such an analysis. The approach taken in this work has been to fabricate a series of GDC single-crystal films of varying thicknesses on Al_2O_3 substrates by RF magnetron sputtering and then to measure their conductivities over the 300-700°C temperature range. These data are analyzed to extract the differences in carrier concentration and activation energy of the single-crystal films as a function of film thickness. An analysis is performed to extract separate activation energies and specific conductivities for the bulk and interface/surface components of the total conductivity. In contrast to the assertions in the literature concerning ultrathin GDC films it is found that as the film thickness is decreased, so that the interface and surface conduction mechanism is more predominate, the total ionic conductivity decreases rather than increases. This data is analyzed in the framework of changes in the temperature-dependent carrier concentration and mobility of the surface and interface regions. Analysis of these data suggests that the temperature-dependent, oxygen non-stoichiometry can significantly affect the ionic conductivity of the GDC surface at temperatures lower than around 600°C. The GDC surface becomes disproportionally resistive at lower temperatures as vacancies are replaced with oxygen atoms, effectively reducing the carrier concentration. This reduction in the surface carrier concentration leads to a drop in total film conductivity by a factor of three from the 500 to 100 nm film at 300°C.

10:40 AM

Q7, Growth of Heteroepitaxial $SrRuO_3$ Electrodes on CeO_2 Buffered R-Plane Al_2O_3 Substrates by RF Magnetron Sputtering: *Madhana Sunder*[1]; Peter Moran[2]; [1]Bruker AXS; [2]Michigan Technological University

A method to integrate single crystal $SrRuO_3$ perovskite thin films on to commercially available r-plane (102) Al_2O_3 substrates, using RF magnetron sputtering, is investigated. Single crystal pseudo-cubic (001) $SrRuO_3$ is a conducting oxide that is of interest for use as a bottom electrode layer for the subsequent integration of functional single-crystal Lead based relaxor perovskite films on to (102) Al_2O_3. The Al_2O_3 substrates have properties that make them a particularly good platform for relaxor ferroelectric in that they have a low microwave dielectric constant and a low dielectric loss. Till date there are no reports of epitaxial (001)c $SrRuO_3$ growths on (102)Al_2O_3 substrates. This can be attributed to the presence of a large ~12% mismatch experienced between the cations positioned along <100>c and <010>c $SrRuO_3$ and Al atoms positioned along <-2-41> and <-221> Al_2O_3 on the (102) Al_2O_3 growth surface. This mismatch can be hypothesized to be reduced by use of intermediate single crystal buffer layers. One such buffer layer is CeO_2 and it has been widely reported to grow with the (001) orientation on (102) Al_2O_3 substrates. However, in the literature, conflicting results exist for $SrRuO_3$ growths on CeO_2 templates i.e. both epitaxial (001)c $SrRuO_3$ films and polycrystalline films with mixed orientations ((110)c,(001)c) have been reported. This has been postulated in the literature to be due to the impact of surface dipole moments on interfacial energies. We interpret these orientation differences to be the result of interfacial

reactions that take place at the CeO_2-$SrRuO_3$ interface and intend to test it by carrying out depositions under identical conditions on a (001) CeO_2 template and separately on a $YBa_2Cu_3O_7$ coated CeO_2 template. The resultant out-of-plane orientation, in-plane epitaxial relationship, film crystallinity and film thickness are characterized by means of a high resolution X-ray diffractometer. The $SrRuO_3$ films are deposited on 2 inch (102)Al_2O_3 substrates using an ultra high vacuum confocal magnetron sputtering system. When $SrRuO_3$ was grown directly on the CeO_2 buffer layer, a polycrystalline (110)c $SrRuO_3$ film with multiple in-plane arrangements resulted. However deposition of a ~2 nm thick (001) $YBa_2Cu_3O_7$ layer prior to $SrRuO_3$ growth resulted in single crystal (001)c $SrRuO_3$ films. The (001)c $SrRuO_3$ films exhibited a clean interface and a smooth surface morphology (0.4 nm RMS for a 10 µm * 10 µm AFM scan). The films also exhibited a (002)c $SrRuO_3$ rocking curve FWHM of 0.71° and is the narrowest FWHM reported to date for $SrRuO_3$ films grown on CeO_2 templates. The data is interpreted as indicating that (001)c $SrRuO_3$ films result due to the $YBa_2Cu_3O_7$ layer preventing an interfacial reaction between $SrRuO_3$ and CeO_2, that would otherwise result in the formation of (110)c $SrRuO_3$.

11:00 AM Student

Q8, Evidence of Ferroelectricity Induced by Epitaxial Strain in Calcium Titanate Thin Films Grown by Molecular-Beam Epitaxy: *Charles Brooks*[1]; Eftihia Vlahos[1]; Michael Biegalski[2]; Carl-Johan Eklund[3]; Craig Fennie[4]; Karin Rabe[3]; Venkatraman Gopalan[1]; Darrell Schlom[4]; [1]The Pennsylvania State University; [2]Oak Ridge National Laboratory; [3]Rutgers University; [4]Cornell University

$CaTiO_3$ has been predicted by first principles to have strain-induced ferroelectricity. With sufficient tensile strain the development of a polar instability is predicted to occur with polarization along a <110> pseudocubic direction relative to the primitive perovskite lattice vectors. Unlike the strain-induced ferroelectricity observed in $SrTiO_3$ for both compressive and tensile strains, only tensile strain is predicted to induce ferroelectricity in $CaTiO_3$ due to large oxygen-octahedron rotations present in the bulk equlibrium phase of $CaTiO_3$ [1]. In accordance with these predictions, we report evidence of a ferroelectric transition in strained (100) $CaTiO_3$ films grown by molecular-beam epitaxy (MBE). When deposited on $NdGaO_3$ and LSAT $(LaAlO_3)_{0.3}$-$(SrAl_{1/2}Ta_{1/2}O_3)_{0.7}$ substrates at epitaxially-induced tensile strains of 1.1% and 1.3% respectively, 20 nm thick films of $CaTiO_3$ exhibit characteristics consistent with ferroelectricity in both second harmonic generation (SHG) and dielectric measurements. At 20 K the $CaTiO_3$ film on LSAT has a remnant polarization of ~5µC/cm^2. The film appears fully commensurate by x-ray diffraction with a substrate limited rocking curve full-width at half max of 9 arc seconds. Both capacitance vs. temperature and SHG intensity vs. temperature results agree that the paraelectric-to-ferroelectric transition occurs around 150 K. SHG also confirms the prediction of the polarization direction being along the psuedocubic perovskite <110> direction. [1] C.-J. Eklund, C.J. Fennie, and K.M. Rabe, Phys. Rev. B 79, 220101(R) (2009).

11:20 AM

Q9, Synchrotron Spectroscopy Detection of Spin-Polarized Bands and Hopping-Induced Mixed Valence for Ti and Sc in GdSc$_{1-x}$Ti$_x$O$_3$ for x = 0.18 and 0.25: *Gerald Lucovsky*[1]; Leonardo Miotti[1]; Karen Bastos[1]; Carolina Amada[2]; Darrell Schlom[3]; [1]NC State University; [2]Penn State University; [3]Cornell University

Ti substituted for Sc in nano-grain and single crystal complex oxide d^0 $GdScO_3$ films is incorporated in a trivalent state, Ti^{3+}, creating a mixed d^0-d^1 oxide with composition-dependent transport properties, including an insulator to metal transition for compositions in which Ti exceeds a percolation threshold of ~ 16%. X-ray absorption spectroscopy has been used to study occupied electronic states of the Ti^{3+} atoms, and final states for 2p to 3d core level excitations, O 1s core level excitations to virtual conduction band states, intra d-level excitations, and resonant photoemission. These spectrocopies are interpreted in the context of many electron transitions and distinguish between spin alignment in nano-grain films, and single crystal films identifying hopping-induced multi-mixed valency on Ti and Si sites in "Sc-oxide" planes. Inter-atomic transport provides a novel approach to modulate ferromagnetism

associated with a double exchange mechanism. i) O K edge X-ray absorption: Comparisons between nano-grain, and epi-thin films demonstrates differences in spin-up and spin-down correlation energy split bands. Second derivative pre-edge spectra indicate a strong spin-up band at low energy, and a weaker spin-up band separated by ~ 1eV in the epi-films. Randomly orientated nano-grains with dimensions < 3 nm, result in a single broad feature that spans width of the two bands in the epi-films. ii) Ti and Sc L$_{2,3}$ spectra for occupied 2p core levels to 3d levels, have identified differences between spectra in alloy films above and below the percolation threshold. Interpretations in the context of many electron charge transfer multiplet methods has identified the steady-state transfer of electrons between occupied Ti^{3+}, and empty Sc^{3+}, states by an intra-layer steady state hopping process: Ti^{3+}, + Sc^{3+}, >/< Ti^{4+}, + Sc^{2+}, equivalently, Ti d^1 + Sc d^0 >/< Ti d^0 + Sc d^1. iii) Resonant photoemission spectroscopy, energy analyzing photoemitted electrons, indicate two resonances for Ti L$_{2,3}$ and Sc L$_{2,3}$ edge valence band spectra. These are distinguished by different energies within the occupied states of the valence band. The Ti L$_{2,3}$ spectra indicate a resonances above $GdScO_3$ valence band: the Ti^{3+} occupied level, and another within the valence band and assigned to Ti^{4+}. The Sc L$_{2,3}$ spectra indicate two resonances as well; one associated with decrease in the concentration of occupied Sc^{3+} states, and the second with increase the concentration Sc^{2+} occupied states. These changes are consistent charge exchange: Ti d^1 + Sc d^0 >/< Ti d^0 + Sc d^1. Finally, the results of this paper indicate the two conditions necessary for double exchange ferro-magnetism, are met by alloying in Ti in Gd(Sc,Ti)O$_3$: (i) mixed valency of in-plane Ti and Sc atoms, and (ii) hopping transport metallic conductivity. Inter-atomic transport then providesa novel way for current controlled double exchange ferromagnetism.

11:40 AM

Q10, Application of Many Electron Charge Transfer Multiplet (CTM) Theory to Band Edge and Band Defect States in High-K Gate Dielectrics and Complex Functional Oxide Thin Films: *Gerald Lucovsky*[1]; Leonardo Miotti[1]; Chung Kwun-Bum[1]; [1]NC State University

The performance and reliability of high-k gate dielectrics, and complex oxides for advanced devices for nano-CMOS and beyond is determined by the densities of intrinsic bonding defects, and defect precursor bonding arrangements. Theoretical studies have addressed O-vacancy defects in transition metal (TM) oxides for gate dielectric applications, e.g., HfO_2 and ZrO_2. However, these have not taken proper account of the strongly correlated character of TM-atom d-states, The defect states energy levels so obtained are inherently flawed: (i) they allow ground state and excited states to have doubly occupancy of electrons, and (ii) they give the erroneous impression that features observed in spectroscopic ellipsometry, and electron and optically excited luminescence are associated with excitations from, and transitions to the top of the valence band. This leads to an incorrect assignment of electronically-active defects: (i) by assigning shallow traps to defect states other than those associated an O-atom, and (ii) by not identifying a fundament relationship between defect states and nano-grain dimensions and thickness constraints. This paper extends many-electron charge transfer multiplet (CTM) methods from transitions in first row TM L$_{2,3}$ spectra in elemental oxides, and to Zr_2 and Y_2O_3 M$_{2,3}$ transitions, O K empty conduction band edge states, and to O-atom vacancy defect states in pre-edge and vacuum continuum regimes. Many electron transitions for d-state transitions (i) at the conduction edge, (ii) in L$_{2,3}$ and M$_{2,3}$ transitions, and (iii) for O-atom vacancy defects characterized by a d^2 state have for the first time been explained by the different, but theoretically equivalent CTM formulations. A vacancy defect is created by removal of a neutral O-atom from a bonding site. Independent of local coordination of O, removal of an O-atom leaves two electrons donated by O-atom TM bonding partners. It is assumed that these electrons are localized on an equivalent TM atom in a d^2 high spin state. For the transitions from this state, final states can be on any of the TM metal atoms bordering the vacancy. This is critical, and agreement with the multiplicity of defects from this final state configuration is more physical than a delocalized distribution that extends the final state wavefunctions well beyond the immediate bounds of the vacancy. An equivalent CTM many electron approach has also been applied to complex oxides; e.g., ABO$_3$ cubic perovskites, where A is a first or second row d^0 TM metal, and B is a normal metal, Sr or Ba, or a d^0 lanthanide rare earth such as

Gd. The contributions from tA and B atoms are sequenced at the conduction band edge and are attributed to the p-d transitions using CTMs. This is consistent with studies of $L_{2,3}$ spectra for ionic compounds such as the CaF_2 and the halides of K.

Session R: ZnO Growth and Doping

Thursday AM   Room: 141
June 24, 2010   Location: University of Notre Dame

Session Chairs: Dimitris Pavlidis, Technische Universitat Darmstadt; Jamie Phillips, University of Michigan

8:20 AM Student
R1, Nucleation Layer Based Optimization of MOCVD Grown ZnO by In Situ Laser Interferometry: *Jens-Peter Biethan*[1]; Laurence Considine[1]; Dimitris Pavlidis[1]; [1]Technische Universität Darmstadt

ZnO is a transparent direct bandgap (Eg= 3.37 eV) semiconductor material suitable for electronic and optoelectronic applications. Because of its unique properties, ZnO has recently attracted strong attention. ZnO has an outstanding high exciton binding energy (60 meV), comparable to GaN high saturation velocity and better radiation hardness. Its applications vary from sensors and piezoelectric mechanical systems, to optical and electrical components. Various reports addressed Metalorganic Chemical Vapor Deposition (MOCVD) grown ZnO layers on substrates such as sapphire, glass and silicon, but only few results exist on its deposition on GaN. The use of GaN as a substrate can pave the way for the combination ZnO based heterostructures i.e. ZnO/ZnMgO with more mature GaN technology. This paper reports the optimization of high temperature (HT) ZnO layers grown on c-plane GaN layers by studying the impact of nucleation layer (NL) thickness. A modified Aixtron 200/4 MOCVD system was used for the growth. One of the benefits of using GaN as substrate for the growth of ZnO is the relatively small a-plane lattice mismatch between GaN and ZnO of less than 1.9%. Our studies showed that direct growth of ZnO on GaN at high temperatures leads in relatively poor material quality as evidenced by layer cracking and poor structural quality. To ensure better material quality we implemented the well established for the growth of III-V semiconductors approach, where a thin low temperature grown nucleation layer is used first followed by high temperature grown ZnO. The NL was grown at a temperature ranging from 420°C to 450°C while the HT growth of ZnO took place at 750°C. Oxygen (99.9999 %) and DEZ (bath temperature 30°C) were used as precursors while the carrier gas was selected to be nitrogen. A homemade in-situ interferometry system was used to optimize the nucleation layer growth thickness and to determine the growth rate. The growth rate for the HT ZnO was found to be ~2 µm/h. The in-situ characterization technique proved to be extremely helpful for optimizing the growth conditions. XRD characterization of ~1µm thick ZnO demonstrated a decrease of FWHM from 129 to 50 arcsec by decreasing the nucleation layer from 60 to 40nm. The corresponding FWHM PL values at room temperature were about 10 nm. A stronger decay of reflectance oscillations with time was observed for thicker nucleation layers indicating increased surface roughness. The Hall mobility of the grown ZnO reached values of 108 cm²/Vs. Based on the measured reflectance thickness oscillations and their degradation during high temperature growth, it was found that the nucleation layer thickness necessary for optimum HT growth of ZnO at 430°C is 40 nm - 50 nm. These results are supported by XRD and photoluminescence measurements.

8:40 AM Student
R2, Influence of Substrate Temperature and Post-Deposition Anneal on Material Properties of Ga-Doped ZnO Prepared by Pulsed Laser Deposition: *Robin Scott*[1]; [1]Arizona State University

Dielectric anti-reflective coatings (ARCs) are widely used to improve the efficiency of solar cells and photodetectors. Transparent conductive oxide (TCO) coatings such as indium tin oxide are highly desirable alternatives to dielectrics. With limited indium resources, much effort has been focused on alternative TCOs

like Ga-doped ZnO. Employing a variety of deposition techniques, many groups are striving to achieve resistivities below $1\times[10]^{(-4)}$ ohm-cm with transmittance approaching theoretical limits. In this study, Ga-doped ZnO films were deposited using pulsed laser deposition (PLD) at 10 mTorr between 25 and 600°C. As-deposited samples were then annealed at 350, 400, and 450°C in either forming gas (FG, 5% H2 in Ar) or vacuum at 1.0×10-6 Torr. Atomic force microscopy (AFM) was used to characterize surface roughness of the as-deposited and 400°C FG annealed films. Although there were no measured differences in root mean square (RMS) roughness values, comparing as-deposited to FG annealed films, the 1×1 µm2 AFM images suggest a coalescing of grains or smoothing of the surface after anneal. TEM images of the film deposited at 200°C reveal no change in bulk crystallography after FG anneal, but the surface is smoother. The total layer thickness has decreased, which is likely attributed to FG etching, consistent with the apparent surface smoothening observed on AFM images. X-ray diffraction (XRD) measurements in the vicinity of the (002) diffraction suggest that films deposited at temperatures of 25 and 100°C have large tensile c-axis strain corresponding to high defectivity, while substantial improvements in quality occur when films are deposited at temperatures ranging from 200 to 500°C. Hall measurements of the as-deposited films show a monotonic increase in carrier concentration with decreasing deposition temperature and substantial increases in both carrier concentration and mobility after anneal in either FG or vacuum. As no discernable differences in structural characteristics were detected by XRD and TEM, this increase in conductivity after FG anneal is attributed to the passivation of the negatively charged oxygen species that create depletion regions at grain boundaries, the breaking of metal oxide bonds at the grain edges, or the activation of dopants in the grains. The changes observed in surface morphology after FG anneal may impact the electrical behavior, but further studies are needed to confirm this. The influence of PLD deposition temperature and post deposition anneal on the material properties of Ga-doped ZnO films was investigated. Films deposited at 200°C and then annealed at 450°C in FG show net carrier concentration of $6\times[10]^{20}$ cm-3 and electron mobility of 30.6 cm2/V·s, corresponding to a resistivity of $3.3\times[10]^{(-4)}$ ohm-cm and a conductivity of 2899 S/cm. Optical transmittance is measured to be greater than 90% over a wide spectral range.

9:00 AM
R3, Epitaxial Electrochemical-Deposition of ZnO on Graphite and p-GaN Substrates: *Kazuyuki Uno*[1]; Yoshinori Ishii[1]; Ichiro Tanaka[1]; [1]Wakayama University

Electrochemical deposition is a convenient and cost-effective method for the crystal growth of ZnO and other oxide semiconductor materials[1]. We have studied on the mechanism of the electrochemical growth of ZnO[2]. The features which we are focusing attention are (1) low growth temperature under 100°C, (2) possibility of nano-scaled selective growth using photo-resist, and (3) high use-efficiency of source material. In this study, we have studied on the epitaxial growth of ZnO by electrochemical deposition on graphite and p-GaN. Graphite substrates employed in this study were highly oriented pyrolytic graphite (HOPG) substrate. p-GaN substrate was an epitaxial thin film grown on sapphire substrates by MOCVD. This study is a demonstration of the growth of ZnO on graphite with no damage as well as the epitaxial growth. ZnO crystals were cathodically deposited using a two-electrode electrochemical cell. The counter electrode was Pt wire, the electrolyte was 0.1mol/L aqueous solution of zinc nitrate, and the deposition-bath temperature was fixed at 70°C. The deposition current density was 0.5mA/cm2 and the deposition time was 40min. During the deposition of ZnO on p-GaN, 325nm HeCd laser was irradiated on the p-GaN surface to supply electrons for electrochemical reaction by generating electron-hole pairs. The deposited ZnO films had strong c-surface orientations. FWHM of X-ray rocking curve measurements around ZnO (002) was evaluated. The results are as follows: ZnO(002)/HOPG(002)=1.4°/1.3°, and ZnO(002)/p-GaN(002)=0.13°/0.098°. X-ray pole-figure measurements were also carried out for the estimation of axial orientation of ZnO. ZnO on p-GaN had 6-fold rotational symmetry in the observation of ZnO(1101) and GaN(1101). On the other hand, ZnO on HOPG didn't have any rotational symmetry in ZnO(1-102) and HOPG(1-102). This result indicates that polycrystalline ZnO was grown on a polycrystalline graphite substrate. These X-ray diffraction results suggest that

the electrochemical growth of ZnO occurred epitaxially even though the growth temperature is under 100°C. Photoluminescence measurements were also carried out. Excitonic emissions, such as D⁰X and its phonon replicas, were observed at 6K. For the ZnO on HOPG, the excitonic emissions could be observed at 220K. On the other hand, for the ZnO on p-GaN, excitonic emissions disappeared over 80K. The thermal quenching property can be explained; the band alignment of ZnO/GaN heterostructure is expected to be staggered[3], so that the thermally excited carriers were separated and recombine non-radiatively with increasing temperature. The feature of current-voltage characteristic supported the staggered type of band alignment. We will present experimental results of the electrochemical deposition of ZnO on pyrolytic graphite sheets (PGSs) and on a thin graphite film which was flaked from HOPG. [1] M.Izaki, *et al.*, Appl.Phys. Lett.68(1996)2439. [2] K.Uno *et al.*, phys. Stat. sol(c) 5 (2008) 3141. [3] Walle *et al.*, Nature 423 (2003) 626.

9:20 AM Student
R4, Control of ZnO Epitaxial Growth via Focused Ion Beam Induced Damage in Lattice-Mismatched Substrates: *Blake Stevens*[1]; Benjamin Myers[2]; Vinayak Dravid[1]; Scott Barnett[1]; [1]Department of Materials Science and Engineering, Northwestern University; [2]NUANCE Center, Northwestern University

A novel method of controlling epitaxy in ZnO films via focused ion beam (FIB) damage of sapphire substrates will be presented. By pre-patterning the substrates with surface lattice damage, crystal orientation can be controlled in subsequent film growth. This eliminates the need for post-deposition treatments to create structural patterning. The concept is demonstrated with the ZnO/Al_2O_3 system, but the method is likely applicable to a range of different epitaxial film/substrate systems. The process efficiency is similar to methods such as electron beam lithography and is much more efficient than typical FIB lithography via surface sputtering or beam induced deposition. In this study patterns on c-plane sapphire substrates were exposed to various ion beam energies and doses using a Ga⁺ ion beam in a FEI Helios NanoLab. Patterns were investigated with different shapes (dots, lines, and boxes) and spacing between damaged regions. ZnO thin films were then deposited on these substrates via dc reactive sputtering. The effect of deposition temperature on crystal structure was investigated, with substrate temperatures ranging from 300°C to 700°C. Film thickness effects were also examined. All films exhibited macroscopic epitaxy as verified by x-ray diffraction. To optimize the FIB induced damage mechanism for this process, the balance between ion range, ion sputtering and ion induced lattice damage was investigated using TRIM calculations. The optimum ion energy is achieved when the maximum amount of damage is induced in the near surface of the substrate with the lowest sputtering yield. Energies in the range of 5-15 keV are preferred to balance the surface defect localization and low sputtering yields at low energy with the high defect generation efficiency at high energy. With 5keV ion beam energy, it was found that the ion induced lattice damage with an area dose of 250µC/cm² was sufficient to inhibit epitaxial growth. The film above the damaged substrate regions was polycrystalline in nature and exhibited a different surface morphology, as verified by SEM, TEM, and FIB imaging. Cross-sectional FIB imaging showed a dramatic difference in structure due to channeling contrast. A smearing of selected area electron diffraction (SAED) patterns of the ZnO film further confirmed the epitaxial disruption when examining irradiated areas compared to non-irradiated areas. Electron backscatter diffraction (EBSD) also showed an orientation shift in the ZnO deposited above damaged areas. Using a beam energy of 8keV, which gives a smaller spot size, a sub-100nm pattern was achieved in the ZnO film. Further studies on substrate temperature as well as the effect and location of implanted Ga will also be presented.

9:40 AM
R5, Properties of Nitrogen Molecules in ZnO: *Norbert Nickel*[1]; Marc Gluba[1]; [1]Helmholtz-Zentrum Berlin für Materialien und Energie

During growth nitrogen can be readily incorporated to achieve alloying or doping. For ZnO, which is a very promising material for blue and UV light emitting diodes and lasers, the use of nitrogen has been suggested to achieve p-type doping. Unfortunately, the doping efficiency is rather low. To attain a sufficient hole concentration the nitrogen content has to exceed the hole concentration by 4 orders of magnitude and a vacuum anneal at high temperatures is required to activate the acceptors and to remove residual hydrogen from the sample [1]. This extremely low doping efficiency can have its origin in a number of effects. First, ZnO displays a native n-type behavior and thus, the responsible donors have to be compensated by nitrogen acceptors. Second, infrared and Raman measurements have shown that the presence of nitrogen in ZnO gives rise to the formation of N-H, N-O, and C=N complexes [2], in addition to the formation of N2 molecules observed by electron spin resonance measurements [3]. The presence of these complexes will effectively lower the doping efficiency. Using density-functional theory, we show that nitrogen molecules are capable of causing the formation of localized states in the band gap of ZnO, thereby contributing to the low doping efficiency in an hitherto unexpected way. It is found that N2 causes localized states in the band gap either by forming an N2O molecule or by breaking a Zn-O bond. ZnO crystallizes in the wurtzite structure and thus N2 can be accommodated parallel to the c-axis or the basal plane with its unique axis. For the former case the equilibrium position of N2 is located in the center of a hexagon and one N atom resides in the same plane as the surrounding oxygen atoms When the N2 molecule is placed parallel to the basal plane two stable configurations are found. In the first configuration the nitrogen molecule forms nitrous oxide (N2O) by breaking a Zn-O bond. For the second, energetically more favorable site, the nitrogen molecule breaks a Zn-O bond thereby pushing the O and Zn atoms towards the interstitial sites. Although the N2 molecule does not form a chemical bond with the ZnO lattice a localized state appear in the band gap at about 170 meV above the valence band. This state is attributed to an oxygen p-orbital. Our results are discussed in the light of p-type doping of ZnO.   [1] A. Tsukazaki, et al., Nature Materials 4, 42-46 (2005). [2] N. H. Nickel, F. Friedrich, J. F. Rommeluère, and P. Galtier, Appl. Phys. Lett. 87, 211905 (2005).[3] N. Y. Garces, L. Wang, N. C. Giles, L. E. Halliburton, G. Cantwell, and D. B. Eason, J. Appl. Phys. 94, 519-524 (2003).

10:00 AM Break

10:20 AM
R6, High-Quality p-Type ZnO Layers Grown by Co-Doping of N and Te: *Seunghwan Park*[1]; T. Minegishi[1]; J.S. Park[1]; I.H. Im[1]; D.C. Oh[2]; T. Taishi[1]; I. Yonenaga[1]; M.N. Jung[3]; J.H. Chang[3]; Takafumi Yao[1]; [1]Tohoku University; [2]Hoseo University; [3]Korea Maritime University

We will report the epitaxial growth of high-quality p-type ZnO layers on Zn-face ZnO substrates by (N+Te) codoping. As-grown ZnO:[N+Te] films show p-type conductivity with a hole concentration of 4×1016 cm-3, while ZnO:N shows n-type conduction. The photoluminescence of ZnO:N shows broad bound exciton emission lines, while ZnO:[N+Te] layers show dominant AoX emission line at 3.359 eV, with a linewidth as narrow as 1.2 meV. Its X-ray linewidth shows narrower line width of 30 arcsec. Detailed investigation of PL properties of (N+Te) codoped ZnO layers suggest that the binding energy of N acceptors lies in a range of 121~157 meV. We note that as-grown (N+Te)-codoped ZnO layers heteroepitaxially grown on sapphire substrates showed n-type conduction, while they were converted into p-type conduction after annealing.

10:40 AM
R7, Magnetic Properties of Mn and N Doped ZnO: *Mathrubhutham Rajagopalan*[1]; S. Ramasubramanian[1]; J. Kumar[1]; [1]Anna University

Transition metal doping in ZnO is being studied extensively both theoretically and experimentally. Room temperature ferromagnetism in Mn doped ZnO was initially predicted but experiments show diverse magnetic properties at low as well as at high temperatures. Double exchange mechanism is proposed to explain ferromagnetism in TM doped ZnO. In the present work the magnetic moment and the magnetic anisotropic energy (MAE) of Mn and N co doped ZnO for two concentrations namely 4.2% and 6.25% are reported. Tight binding linear muffin-tin orbital method and full potential linear augmented plane wave methods are used. The calculations are based on the density functional theory and local spin density approximation. A periodic 2X2X2 and 2X2X3 wurtzite supercell containing 32 and 48 atoms in a unit cell was used. One or two atoms of Zn and O atoms were substituted by Mn and N atoms which give a concentration of 4.2% and 6.25% respectively. Spin polarised electronic

structure calculations are performed and the magnetic moments at Zn, Mn, O and N sites are calculated. For 4.2% concentration the magnetic moments at Mn and N sites are 3.80 μB and -0.07 μB and for 6.25% they are 3.90 and -0.06 μB respectively. The total magnetic moment at 4.2% and 6.25% are 4.00 and 4.20 μB. The total density of states are also calculated for both the spins and are given below. It has been concluded that 4.2% concentration is half metallic whereas 6.25% is metallic. The magnetic anisopropic energies for the various directions namely [0001], [1100], [1000] and [0100] are calculated for both the concentrations. The MAE is maximum for 4.2% along [0001] direction and the value is 1376.16 J/m**3 whereas for 6.25% along the same direction it is 1047.597 j/m**3. It is concluded that 4.2% concentration of Mn and N codoped in ZnO can be used in spintronic devices and the easy magnetising direction is [0001].

11:00 AM

R8, Effects of p-Type Doping on the ZnO Based Diluted Magnetic Semiconductor Thin Films: *Liping Zhu*[1]; Xuetao Wang[1]; Zhigao Ye[1]; Zhizhen Ye[1]; [1]Zhejiang University

Co-N and Ni-Na co-doped ZnO thin films were fabricated on Si(100) and quartz substrates using pulsed laser deposition technique and the influence of p-type doping on the conduction and magnetism of ZnO based thin films were studied. The thin films obtained at optimal condition show magnetism at room temperature. We examined the samples by XRD, SEM, XPS, Hall testing and superconducting quantum interference device (SQUID) magnetometry. The results indicate that the configuration of the thin films is a completely c-axis orientation wurtzite crystal without any Co or Ni related phases. Co and N atoms substitute Zn and O sites in the form of CoZn and NO for the Co-N co-doped samples, while Ni and Na atoms existing in the form of NiZn and NaZn for the Ni-Na co-doped samples. Hall testing and SQUID results indicate that the Co-N and Ni-Na co-doped thin films are p type with higher carrier concentration and magnetization than the Co and Ni doped ZnO thin films respectively. The doped N or Na changes the conduction type and gives rise to the increasing of magnetization of the ZnO based thin films.

11:20 AM Student

R9, Hydrothermal Synthesis of Wide Bandgap Be$_x$Zn$_{1-x}$O Nanorods for Solar Blind Photodetection: *Ke Sun*[1]; Shrey Prasad[1]; Joe Lee[2]; Bob Olah[3]; Achyut Dutta[3]; Deli Wang[1]; [1]University of California, San Diego; [2]Tanner Research Inc; [3]Banpil Photonic

ZnO is one of the most investigated wide band gap metal oxide, which finds its successful applications in optoelectronics, such as light emitting devices, photovoltaics, photodetectors, and field emission. The formation of nanowires enables charge separation between the nanowire center and the surface, the enhanced carrier lifetime and consequently much increased light responsive for high sensitivity photodetector applications [1]. Mg$_x$Zn$_{1-x}$O alloys are broadly studied as solar blind photodetectors for military and aerospace applications. By increasing the Mg atomic fraction to x~0.44, the bandgap can be around 4.2eV, leading to the solar blind region. However, crystal phase segregation between ZnO and MgO was observed for Mg concentrations x>0.36, due to the different crystal structures and large lattice mismatch between hexagonal ZnO and cubic MgO [2]. On the other hand, the value of the energy band gap of BeZnO can be efficiently engineered to vary from the ZnO band gap (3.4eV) to that of BeO (10.6eV) [3]. Both ZnO and BeO are hexagonal crystal structure and the a-axis lattice constant values for ZnO and BeO are 3.249 and 2.698 Å, respectively, which is much less than the MgO and ZnO case. In this study, we report our research progress on low temperature synthesis of Be$_x$Zn$_{1-x}$O nanorods from a mixture solution of beryllium and zinc salt. Two seeding process are studied: 1) decomposing of beryllium nitrate and zinc acetate alcohol solution at temperature higher than 250°C in Ar/N$_2$ environment produces BeO and ZnO textured seeds [4] for BeZnO nanorods to grow; 2) we also tested is using sputtered ZnO thin film as seeds. Similarly to hydrolysis of Zinc acetate with addition of hexamethylenetetramine (HMTA) for Zn nanowire growth, beryllium nitrate forms tetrahedral beryllium hydroxide with addition of alkalis which is soluble in excess of hydroxide ions thermally released from HMTA. Then, decomposition of Be(OH)$_2$ and Zn(OH)$_2$ in aqueous solution forms Be$_x$Zn$_{1-x}$O

alloy, where the Be concentration is controlled by the initial Be salt concentration in the solution. Higher decomposition temperature (>110°C) is realized by modifying the Ethylene glycol concentration in water. The optical transmission measurement of nanorods array is studied using iHR550 spectrometer mounted with deuterium UV light source. Bandgap of synthesized nanorods is directly calculated from $(\alpha h\upsilon)^2$ vs. $h\upsilon$ plot [5], where a is the absorption coefficient with respect to average length of nanorods. Since Be has light atoms, its concentration is then determined from the calculated bandgap without using sophisticated equipments. Due to the limit of current UV light source (lowest wavelength 200nm), theoretically the maximum Be concentration that can be measured is 39%. To further improve the aspect ratio of the nanorods, surfactant (Polyethylenimine Mw~800) effect [6] is also investigated.

11:40 AM Student

R10, Synthesis and Charaterization of p-NiO/n-ZnO Heterojunction Diode by Spray Pyrolysis: *Namseok Park*[1]; [1]UCSD

Namseok. Park, Ke, Sun, and Deli, Wang Department of Electrical and Computer Engineering, University of California, San Diego, California 92093-0407, USA We report *p-n* heterojunction diodes composed of transparent oxide semiconductors, *p*-NiO and *n*-ZnO. Transparent oxide thin films of NiO/ZnO were deposited on pre-heated ITO glass substrates using a chemical spray pyrolysis technique. Nickel chloride hexahydrate (NiCl$_2$·6H$_2$O) and Zinc acetate dihydrate (Zn(CH$_3$COO)$_2$) were chosen as a precursor for the deposition of NiO and ZnO, respectively. The NiO/ZnO *p-n* heterojunctions were fabricated by depositing a ZnO layer on NiO layer sequentially. Films are deposited on various conditions. The effect of substrate temperature and solution concentration on the thin films was investigated by structural, electrical and optical properties of films. The as-prepared NiO films were thin gray in color, uniform and strongly adherent to the substrate. The thickness of films was varied from 200 nm to 300 nm. The surface morphology and optical property of fabricated heterojuction were examined by scanning electron microscopy and spectrometer. The NiO thin film was uniform, homogeneous and with a distribution of fine crystallites except for a very few linearly interlinked small particulates embedded over the smooth surface. ZnO thin films demonstrated a better surface smoothness than NiO. We observed that there existed a homogeneous distribution of quite small grains with edge-like shape. The sample prepared at a higher deposition temperature showed smoother surfaces. This is obviously the result of a decrease of the average crystal size by surface diffusion. It was of great importance to minimize the variation of surface morphology of thin films in order to reduce a leakage current at the *p*-NiO/*n*-ZnO heterojunction and contacts. NiO thin films with a transmission up to 75% and absorption less than 2% were obtained. It could be noticed that the ZnO thin films had a high optical transmittance above 90% and also they had an optical absorbance almost zero in the visible range. The average optical transmittance of the heterojunction diode was 80% in the visible range. A silver metal was formed on top of ITO and *n*-ZnO layers to make Ohmic contact between the metal and films to measure electrical properties. The current-voltage measurements of a *p*-NiO/*n*-ZnO heterojunction diode were performed in the dark and under illumination at room temperature. The device demonstrated a clear rectifying behavior with a typical forward-to-reverse current ratio of 10 in the range of -5 to +5 V. The reverse dark current of this device was 30 nA at -5 V. In addition, an apparent forward threshold voltage occurs at 2.5 V.

Session S: Light Emitting Diodes and Laser Diodes

Thursday AM   Room: 155
June 24, 2010   Location: University of Notre Dame

Session Chairs: Russell Dupuis, Georgia Institute of Technology; Theeradetch Detchprohm, Rensselaer Polytechnic Institute

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8:20 AM

S1, Effect of Inaln Electron Blocking Layer in Visible Light-Emitting Diodes on Quantum Efficiency Grown by Metalorganic Chemical Vapor Deposition: *Hee Jin Kim*[1]; Suk Choi[1]; Seong-Soo Kim[1]; Jae-Hyun Ryou[1]; P. Yoder[1]; Russell Dupuis[1]; Kewei Sun[2]; Alec Fischer[2]; Reid Juday[2]; Fernando Ponce[2]; [1]Georgia Institute of Technology; [2]Arizona State University

In this study, we proposed active-layer-friendly InAlN layers which which are lattice-matched to GaN as an electron blocking layer (EBL) for visible III-nitride-based light-emitting diodes (LEDs), and investigated the effect of EBL on efficiency droop. The lower growth temperature, higher conduction band offset, and lattice-matching capability of these InAlN layers are considered to enhance the quantum efficiency of visible LEDs such as blue or green LEDs than conventional AlGaN EBLs by reducing thermal damages of the active layer during EBL growth, providing more electron confinement effect and reducing strain induced defect generation. All epitaxial layer structures were grown by low-pressure metalorganic chemical deposition in a Thomas Swan Scientific Equipment 6×2" reactor system on c-plane sapphire substrates. The LED structures consist of a 3-µm-thick Si-doped GaN layer with an electron concentration of n~5×10^{18} cm^{-3}, a five-period InGaN/GaN (2.5/11 nm) multiple quantum well (MQW) active region, a 20-nm-thick Mg-doped $In_{0.18}Al_{0.92}N$ EBL, a Mg-doped $In_{0.03}Ga_{0.97}N$ layer with a hole concentration of p~2×10^{18} cm^{-3}, and a Mg-doped $In_{0.03}Ga_{0.97}N$ contact layer with a doping concentration of [Mg]~1×10^{20} cm^{-3}. Two kinds of lattice-matched InAlN EBL layers were employed in LED structures with different growth conditions. One was grown at 840°C and 300 Torr (labeled as HT-InAlN EBL) and the other was grown at 780°C and 75 Torr (labeled as LT-InAlN EBL). The growth rate of LT-EBL is 0.065 nm/s which is faster than HT-EBL of 0.013 nm/s. LED with a HT- or LT-InAlN EBL show higher EL intensities in EL intensity than LED without InAlN EBL. This result indicates that the InAlN EBLS is effectively confining electrons by preventing them from escaping the MQWs, leading to the improved quantum efficiencies in the green LEDs. Comparing luminous efficiencies between LEDs with HT-EBL and LT-EBL, the integrated EL intensity of LED with LT-EBL is 30% brighter than that of LEDs with the HT-InAlN EBL at J=40.8 A/cm^{2}. Since LT-EBL growth happens at higher rates and shorter times, our observations suggest that thermal damage in the active layer may have a significant influence on the device efficiency. We also compared device performance of LED with InAlN EBL with LED with conventional AlGaN EBL. By measuring EL at pulse mode, InAlN EBL is more effective in enhancing quantum efficiency as well as in reducing efficiency droop than conventional AlGaN EBL. Detailed experimental results on quantum efficiency and efficiency droop in blue and green LEDs with various EBLs will be presented.

8:40 AM Student

S2, Fabrication of GaN-Based Laser Diode and Laser Diode Facet Formation: *Wenting Hou*[1]; Wei Zhao[1]; Mingwei Zhu[1]; Theeradetch Detchprohm[1]; Christian Wetzel[1]; [1]Rensselaer Polytechnic Institute

GaN-based materials have gained high interest for the fabrication of green, blue and UV light emitting diodes (LEDs) and laser diodes (LDs). Recent remarkable progress towards green laser diodes by several groups has accelerated the field. Here we discuss aspects of our approach to fabricate green laser diodes, namely epitaxial ridge re-growth, metal waveguiding, and focused ion beam (FIB) coupling mirror formation. The conventional way to form a laser current injection ridge is by etching after photolithography. However, there is ample evidence of ion damage to the active region by the high energy ions in ICP/RIE or CAIBE etching. A promising alternative is the selective re-growth of p-GaN

and p-AlGaN cladding layer ridge within the openings of a SiO_2 mask. With good optimization, the re-growth results in smoother sidewalls of the ridge than either of the etching processes. Cracking typically observed in AlGaN layers of high AlN fraction on GaN are found to be readily suppressed in the re-growth process of the µm-wide ridge stripes. At the present stage of development, however, a higher forward voltage of 20 V is observed when compared to etched ridge samples at 8 V at the same current of 8 mA (equivalent a current density of 102 A/cm^{2}) Inconsistency of the p-GaN doping in the re-grown layers is a possible reason, and further optimization is warranted. Optical characterization of a LD structure usually is hindered by the upper cladding layers and p-contact regions. It therefore seems desirable to complete an LD structure only after the active QW region proves promising as determined by optical gain characterization. To this end, LD structures employing a metal mirror are a suitable supplement to complete the optical resonator. Here we employ a layer of silver on top of the p-layers of the ridge and find a substantial reduction in forward voltage and an increase in light output power. The silver mirror enhances the light output power, particularly at the shorter wavelength portion of the emission spectrum. The FWHM of this peak decreases as the current increases, making this the most likely wavelength of anticipated lasing emission. Crystal cleaving is the most straight forward approach for laser mirror formation. Yet, for accurate length control of the cavity, a combination of ICP/RIE etching with focused ion beam milling is a desired alternative for the formation of the second mirror. Here we demonstrate results of various development stages of the laser mirror formation.This work was supported by a DARPA VIGIL program through the United States Air Force AFRL/SNH under FA8718-08-C-0004. This work was also supported by the National Science Foundation (NSF) Smart Lighting Engineering Research Center (# EEC-0812056).

9:00 AM

S3, Performance Improvement of AlInGaN Visible Laser Diodes by Epitaxial Layer Design: *Jianping Liu*[1]; Jeomoh Kim[1]; Zachary Lochner[1]; Seong-Soo Kim[1]; Yun Zhang[1]; Jae-Hyun Ryou[1]; Shyh-Chiang Shen[1]; P. Yoder[1]; Russell Dupuis[1]; Kewei Sun[2]; Alec Fischer[2]; Reid Juday[2]; Fernando Ponce[2]; [1]Georgia Institute of Technology; [2]Arizona State University

AlInGaN-based blue and green laser diodes (LDs) are of interest for applications in full-color displays. We investigated the effect on the performance characteristics of LDs of epitaxial layer design in two aspects: (1) the effect of an electron blocking layer (EBL) by comparing a typical AlGaN EBL with an abrupt step interface from last quantum-well barrier (QWB) and a combined grading/step EBL with compositional grading from last quantum well (QW), and (2) the effect of optical waveguide layers (WGLs) by comparing GaN and InGaN WGLs. We used a graded composition (grading from the InGaN last QW to the AlGaN EBL) in the AlxGa1-xN EBL instead of a constant Al composition used in the conventional EBL design. As a result of the EBL epitaxial layer design change, the device performance shows a reduced threshold current density as well as a higher slope efficiency for LDs using a graded-composition EBL. We believe the graded EBL mitigates band bending in the last GaN QWB and AlGaN EBL caused by the spontaneous and piezoelectric polarization. The grading/step EBL design is expected to enhance carrier (especially hole) distribution in the MQWs for improved LD performance. In addition, the grading/step EBL design is expected to suppress the electron inversion layer that is formed near AlGaN EBL. Due to the smaller difference of refractive index between AlGaN and GaN materials as the wavelength increases, the optical confinement of the waveguide becomes smaller in blue and longer-wavelength LDs. We used InGaN layers for the WGL in blue and longer-wavelength LDs to utilize the larger refractive index contrast for InGaN compared to GaN. The effects of the InGaN waveguide layers on the optical properties are investigated by comparing LDs with GaN and InGaN WGLs. The advantage of enhanced radiative recombination efficiency using InGaN WGLs was also observed in addition to improved optical confinement. The spontaneous EL peak intensity at 50 mA for the LDs with $In_{0.03}Ga_{0.97}N$ waveguide layers is 80% higher than that of the LDs with GaN waveguide layers. Moreover, the FWHM of the EL at 50 mA for the LDs with $In_{0.03}Ga_{0.97}N$ waveguide layers is 27.8 nm, 6 nm lower than that of the LDs with GaN waveguide layers. LDs with $In_{0.03}Ga_{0.97}N$ waveguides lase (pulsed) at λ =454.6 nm at 300K. The threshold current density Jth is 3.3

kA/cm^{2} and the threshold voltage is 5.9V. The use of these waveguide designs in the development of longer-wavelength (green) LDs will also be discussed.

9:20 AM Student

S4, Enhancement of the Light-Extraction Efficiency of GaN-Based Light-Emitting Diodes Using a Graded-Refractive-Index Layer: *Byung-Jae Kim*[1]; Joona Bang[1]; Sung Hyun Kim[1]; Jihyun Kim[1]; [1]Korea University

The light extraction of light-emitting diodes (LEDs) was limited by total internal reflection (TIR), which is caused by the large contrast of the refractive index between air (n=1) and GaN (n=2.5). Recently, graded-refractive-index (GRIN) anti-reflection (AR) layer was widely used for increasing the light extraction efficiency by reducing the Fresnel reflection of photons. The refractive index was gradually controlled from the refractive index of GaN to the refractive index of air in GRIN structures. Indium tin oxide (ITO) and TiO2 have been widely used as the materials of GRIN layer due to their transparency. In this study, benzocyclobutene (BCB) was employed as the material of AR layer due to its high optical transparency (>90%) and simple processing scheme as spin-coating technique. Also, BCB was chemically and mechanically very stable material. We fabricated GRIN AR layer by nanospheres lithography (NSL) using SiO2 nanospheres. Firstly, a BCB film with the thickness of 200nm was spin-coated on the LEDs. Then, SiO2 nanospheres with the diameter of 250nm were spin-coated on BCB layer. The sample was heated at 160°C for 5 seconds, so the bottom half of SiO2 nanospheres was embedded into the BCB layer. Then, SiO2 nanospheres were removed by wet etching using HF-based solution. Consequently, the porous BCB layer with the porosity of 70% was fabricated on the BCB layer, so GRIN BCB layer consisted of two layers as BCB layer (n=1.55) and porous BCB layer (n=1.2). GRIN BCB layer was effective to enhance the light extraction efficiency of LEDs due to the reduction of Fresnel reflection and the side wall emission. The optical data as photoluminescence (PL) and electroluminescence (EL) was compared between LEDs samples with/without GRIN BCB layer. The room temperature PL intensity was increased by 29.7% and 61.3% after fabricating BCB layer and GRIN BCB layer on LEDs. Also, the light output at injection current of 10mA was increased by 9.2% and 22% after fabricating BCB layer and GRIN BCB layer on ITO layer of LEDs, respectively. The details about the experiments and the results will be presented.

9:40 AM Student

S5, Nano-Fabrication of Green AlGaInN LEDs – Structural Wavelength Control and Enhanced Light Extraction: *Christoph Stark*[1]; Theeradetch Detchprohm[1]; Christian Wetzel[1]; [1]Future Chips Constellation, and Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, Troy, New York, USA

Light emitting diodes (LEDs) are normally grown on large wafers and despite strict process control the final emission wavelength can be inhomogeneous across a wafer. This poses a challenge where LEDs with a precisely known color are needed. An ideal solution would be to shift the wavelength after the wafer is grown. Here, green AlGaInN LEDs, grown by MOVPE, are investigated for the possibility to tailor the internal piezo-electric fields and thereby fine tuning the emission wavelength after the growth. This potentially can be achieved by spatial patterning of the wafer on the nano- to micro-meter range. The patterns investigated consist of "finger structures" with up to 100 nano-patterned LEDs connected to a common contact pad. Typical dimensions of the total device area are 150 µm x 100 µm, whereof the "fingers" have a length of 100 µm. The width and spacing are changed for different devices. These structures are generated by electron beam lithography in PMMA photo resist and a durable Nickel hard mask (70 nm) is obtained by electron beam evaporation and a lift-off technique. This metal layer also serves as top contact to the nano-LEDs and eliminates the need to contact the LEDs individually. The pattern is transferred to the LEDs by an inductively coupled plasma (ICP) mesa etch that penetrates through the active region. The nano-LED device geometry is characterized by scanning electron microscopy (SEM) and voltage-current curves are recorded. Sloped sidewalls are observed which increase the device dimensions. If a constant surface leakage current is assumed, the reverse leakage current density for the devices must increases with smaller dimensions, which is in accordance with IV data. The electroluminescence (EL) for devices with structures down to 200

nm is found to have no wavelength shift relative to devices with 1 µm width. But for the smallest realized patterning dimension of 51 nm, a blue shift in the EL is observed at constant current density of 0.03 kA/cm^2. This supports the feasibility of our approach and we pursue further shrinking of the structure size. Observations by optical microscopy show that the EL of nano-patterned region appears 4 times brighter than the region of the device that is used as a contact pad. This can be explained by a higher light extraction efficiency which results from the increased scattering in this unique device design or by an increased internal efficiency due to a reduced number of defects in the nano-patterned LEDs. Acknowledgements: This work was supported by the National Science Foundation (NSF) Smart Lighting Engineering Research Center (# EEC-0812056).

10:00 AM Break

Session T: AlGaN Growth and Devices

Thursday AM   Room: 155
June 24, 2010   Location: University of Notre Dame

Session Chairs: Theeradetch Detchprohm, Rensselaer Polytechnic Institute; Russell Dupuis, Georgia Institute of Technology

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10:20 AM Student

T1, Polarization Induced p-Doped Nitride Quantum Well UV LEDs: *Jai Verma*[1]; John Simon[1]; Vladimir Protasenko[1]; Debdeep Jena[1]; [1]University of Notre Dame

UV LEDs can provide compact sources for uses in microscopy, high density optical storage, studying chemical reactions, and water purification. They can be used to irradiate fluorescent materials to produce broadband emission. III-V nitride AlGaN alloys span a wide range of band gaps from 3.4 eV for GaN (UV) to 6.2 eV for AlN (deep UV). Thus AlGaN based device structures can be utilized to produce light of energy higher than GaN band gap energy. But wide bandgap semiconductors suffer from poor p-type doping owing to large activation energy for Mg dopant. The activation energy increases from 200 meV for GaN to 650 meV for AlN. This is much higher when compared to thermal excitation energy at room temperature (26 meV). III-V nitrides also have large built-in polarization field with spontaneous and strain induced piezoelectric components. GaN QWs have been incorporated into p-n junction UV LED structures that did exploit polarization-induced p-type doping, but had no such wells. Compositionally grading GaN to AlGaN on N-face GaN substrate had led to polarization induced p-type doping. Improved p-type doping resulted in efficient hole injection into the active layers giving higher EL intensity. Moreover, the graded layer provided an electron barrier which is evident by the band diagram. The UV LEDs studied here were grown on n-type N-face GaN free-standing substrates by Plasma Assisted Molecular Beam Epitaxy (PAMBE). Free standing GaN substrates have low dislocation densities (~5e7 cm^{-2}) ensuring low non-radiative recombination rates. An initial growth thermocouple temperature of 600°C is used which is then gradually increased to 660°C and decreased back to 600°C. The nitrogen RF power is kept at 275W throughout the growth. To achieve compositional grading, the Al cell temperature is increased using a computer program while keeping the Ga cell temperature constant. Si and Mg are used for n- and p-type doping. X-ray Diffraction (XRD) and Atomic Force Microscopy (AFM) studies indicate that the intended graded layers and intended GaN quantum wells embedded in AlGaN barriers was successfully realized. We perform mesa etch using ICP and, deposit Ni/Au for p-type contact and Ti/Au for n-type contact to process the grown structures into UV LEDs. The Electroluminescence (EL) spectrum obtained for the GaN QW structure at an injection current of ~75 mA shows a peak at 380 nm, with a shoulder in the spectrum which extends to wavelengths below 360 nm. The emission at energies higher than the bandgap energy of GaN can be attributed to recombination in the graded AlGaN layer. This observation of successful incorporation of quantum wells, and electroluminescence from

AlGaN regions indicate that $Al_xGa_{1-x}N$ QWs and $Al_yGa_{1-y}N$ barriers can now be used to obtain respectable emission intensities for deeper UV or higher energy photons.

10:40 AM

T2, Structural Characterization of Highly Conducting $Al_xGa_{1-x}N$ (x >50%) for Deep Ultraviolet Light Emitting Diode: *Joseph Dion*[1]; Bin Zhang[1]; Qhalid Fareed[1]; Asif Khan[1]; [1]Nitek, Inc.

Research interest in the III-Nitride deep ultraviolet (UV) light emission devices has significantly increased over the past few years. Their potential as a replacement for mercury lamps in several bio-medical, air-water purification and germicidal systems is one of the key drivers for this research. Due to the transparency requirements, the substrate choices for the sub-300 nm AlGaN deep UV surface emission devices, such as light emitting diodes (LEDs), are limited to either single crystal sapphire or AlN. The $Al_xGa_{1-x}N$ multiple quantum well (MQW) based deep UV light emission devices over either of these two substrate types require heteroepitaxy. Highly conductive, high composition (>50%Al) nAlGaN layers are critical to the development of high power deep ultraviolet light emitting diodes. The development of these layers is plagued by the tendency of AlGaN films grown on sapphire to crack. This limits the thickness, and therefore conductivity, that can be achieved. Previous research has shown the beneficial effect of inserting an AlN/AlGaN superlattice (SL) on AlN buffers layers to mitigate cracking1. In this research, the strain relaxation of AlGaN films grown on AlN/Sapphire templates was investigated by off-axis reciprocal space mapping (RSM). Four samples are compared in this study. All samples include a standard AlN buffer layer on sapphire, comprising a high temperature annealing step followed by low temperature AlN nucleation layer and high temperature AlN Pulsed Atomic Layer Epitaxy (PALE) layer. Sample A is a continuous growth of the AlN buffer layer followed by an AlN/AlGaN SL, a thin undoped AlGaN layer and thick silicon doped nAlGaN layer. For Sample B, a template was grown up to the thin undoped AlGaN layer. This template was then used for growth of a thick nAlGaN layer. For Sample C, the same nAlGaN layer was grown directly on a previously grown AlN buffer layer. For Sample D, an AlN/AlGaN SL, a thin undoped AlGaN layer and thick silicon doped nAlGaN layer were grown on a poorer quality AlN buffer layer. The results indicate the nAlGaN films growing on AlN on sapphire templates initially grow in compression, nominally lattice matched to the relaxed AlN buffer layer. This compressive strain is gradually relieved during the course of the thick nAlGaN growth. Relaxed, uncracked nAlGaN films can be grown on high quality AlN layers, with or without inserting a SL. The growth interruption in Samples B and C appears to allow the growth of an unstrained nAlGaN layer without a gradual release of compressive strain. However, on poor quality AlN layers, even the insertion of a superlattice does results in less compressive strain relief. The results will be discussed in detail.

11:00 AM

T3, Epitaxial Growth and Doping of AlGaN Alloys on AlN Single Crystal Substrates: *Ramón Collazo*[1]; Seiji Mita[2]; Jinqiao Xie[2]; Anthony Rice[1]; James Tweedie[1]; Rafael Dalmau[2]; Zlatko Sitar[1]; [1]North Carolina State University; [2]HexaTech, Inc.

As the building blocks of current deep UV light emitting diode technology and high-power electronic devices, AlGaN alloys have attracted considerable attention. In this study, AlGaN films with varying compositions and doping levels were deposited on homoepitaxial AlN layers grown on AlN single crystal substrates. The mismatch between film and substrate causes a compressive strain within the AlGaN layers, varying with composition. Typical engineered relaxation methods include controlled dislocation nucleation or "bending" of existing dislocations from the substrate to provide for the misfit component. Nevertheless, these relaxation mechanisms are based on introducing dislocations into the films which could have an adverse effect on electronic performance. If relaxation is not essential for a given application, relaxation schemes can be avoided altogether in favor of pseudomorphic AlGaN films on AlN. However, this approach may limit the practical range of AlGaN compositions for pseudomorphic structures. In order to study this effect and the effects on n-type doping, AlGaN films of compositions above 60% Al content and thickness

around 400 nm were grown by MOVPE on templates consisting of 200 nm thick c-plane homoepitaxial AlN layers on AlN substrates. For the templates, after nitridation of the AlN substrate surface, 200 nm thick AlN films were deposited at a temperature of 1220ºC in a mainly hydrogen atmosphere. AlGaN layers were then deposited at a temperature of 1100ºC by introducing the Ga precursor. Structural characterization was performed by acquiring on- and off-axis x-ray diffraction ω-rocking curves, indicating that the films followed the mosaic structure of the substrate. The reflections in a ω-2θ scan from the (002) planes of AlN and AlGaN can be observed along with Pendellösung thickness fringes around the AlGaN peaks of films with compositions above 80% Al. The occurrence of these fringes was qualitatively attributed to the high quality of the films and interfaces. A partial relaxation of 8% was only observed for the AlGaN film with 65% Al content and 400 nm thickness. For compositions above 65% Al, the films were pseudomorphic. A reciprocal space map of the asymmetric (105) reflection from an AlGaN film with 88% Al content indicated no relaxation. A comparison of the room temperature resistivity of different AlGaN alloy compositions grown on AlN and sapphire substrates with a constant Si doping level of 6×10^{18} cm^{-3} was established. AlGaN films grown on AlN substrates consistently exhibited a lower n-type resistivity than those grown on sapphire. An n-type resistivity of 0.1 Ω cm was obtained for an AlGaN film with 80% Al content. The carrier activation energy as a function of Al content in AlGaN for these n-type films was measured. The observed trends will be discussed in light of impurity potential screening and the expected activation energy.

11:20 AM Student

T4, Morphological Development of Homoepitaxial AlN Thin Films Grown by MOCVD: *Anthony Rice*[1]; Ramon Collazo[1]; Seiji Mita[2]; James Tweedie[1]; Jinqiao Xie[2]; Rafael Dalmau[2]; Zlatko Sitar[1]; [1]North Carolina State University; [2]HexaTech, Inc.

AlN thin films were grown on single crystalline (0001)-oriented, Al-polar AlN substrates by metalorganic chemical vapor deposition (MOCVD) to determine the effects of deposition parameters on the thin film microstructure. AlN deposition was conducted at 1100–1250°C under 20 Torr total pressure in H_2 diluent. Trimethylaluminum and ammonia were used as precursors with V/III ratios of 250-500. Triple axis high-resolution x-ray diffraction measurements of the (0002) Bragg peaks of AlN thin films indicated that the films were epitaxial and strain-free. Atomic force microscopy characterization suggests step-flow growth with bi-layer terrace widths of 40 nm and 130 nm for AlN films deposited at 1100°C and 1250°C, respectively. Periodic crystalline faceting was observed with alternating high symmetry (0001) facets and high Miller index facets. The periodic spacing of such facet arrays varied from 80 nm to 450 nm for substrates miscut relative to (0001) by 13° and less than 1°, respectively. Hexagonal pits of up to 800 nm width and 400 nm depth were observed in AlN homoepitaxial thin films deposited at 1100°C. Such pits exhibited an inverted hexagonal pyramid morphology with sidewalls inclined ~45° relative to the surface normal for films deposited on (0001)-oriented substrates. For substrates miscut 13° from (0001), the inclination of pit sidewalls perpendicular to the miscut direction became ~30° or ~60° relative to the surface normal. The average dimension of such pits was found to increase with epitaxial film thickness for AlN deposited at 1100°C: the average pit widths were 400 nm, 600 nm, and 800 nm for film thicknesses of 1 μm, 2 μm, and 3 μm, respectively. No pitting was observed in homoepitaxial AlN thin films deposited at 1250°C. However, pit formation was also observed for multi-layer AlN thin films that consisted of an AlN layer deposited at 1250°C and a subsequent AlN layer deposited at 1100°C. The pit dimensions observed in such multi-layer AlN thin films were found to depend only on the thickness of the layer deposited at 1100°C and were similar to pit dimensions in single-layer AlN thin films of equal thickness deposited at 1100°C. These results are consistent with observations of V-shaped defects in other III-nitride materials in which treading dislocations possessing an edge component intersecting the crystal surface may yield hexagonal pitting. Increasing the radius of curvature of bi-layer terraces by increasing the deposition temperature was found to inhibit the formation of such pits, as predicted by capillary equilibrium theory, but does not prevent the later formation of pits during subsequent deposition at lower temperatures.

11:40 AM Student

T5, Aluminum Gallium Nitride Alloys Grown via Metal Organic Vapor Phase Epitaxy Using Digital Alloy Growth Technique: *L Rodak*[1]; D. Korakakis[1]; [1]West Virginia University

Deep Ultra Violet (UV) emitters are of particular interest for applications including, but not limited to, biological detection and sterilization. Aluminum Gallium Nitride ($Al_xGa_{1-x}N$) alloys are of well suited for UV applications due to the wide direct bandgap that spans the UV range unlike any other direct semiconductor. When grown via Metal Organic Vapor Phase Epitaxy (MOVPE), Al containing alloys are inherently difficult to grow due to the short diffusion length of the Al species and also the high reactivity of the Al containing precursors [1]. This requires high growth temperatures and low reactor pressures when compared GaN growth conditions. As such there has been considerable interest in the development of alternative growth techniques which yield high quality $Al_xGa_{1-x}N$ films [1]. Additionally, strain management in $Al_xGa_{1-x}N$ containing structures is challenging due to the large lattice and thermal mismatches between the binary components. Strain engineering is important to minimize or eliminate certain defects detrimental to device efficiency, such as dislocation or crack formation, and also due to the influence it has on band engineering in this piezoelectric material system [2]. Therefore the development of strain compensating growth techniques remains of critical importance for the fabrication of high quality devices. This work investigates the use of a digital alloy technique as a viable growth method for $Al_xGa_{1-x}N$ alloys and also the influence of different buffer layers on the growth. Digital alloy growth, often called short period superlattices, consists of layers of binary or ternary alloys with a period thickness of a few monolayers (ML) and has previously been reported to be a suitable means of growing III-Nitride alloys [1,3], although most commonly employed in MBE growth. This work targets AlN/GaN superlattices grown on sapphire substrates via MOVPE. The effective AlN mole fraction is varied from 0.2 to 0.9 by adjusting the thickness of the AlN layer. Specifically, the superlattice structures under investigation contain approximately 4 ML of GaN and 1 ML or more of AlN. High resolution X-Ray Diffraction (XRD) is used to determine the superlattice period and c-lattice parameter of the structure, while off-axis XRD reciprocal space maps are used to determine the a-lattice parameter and evaluate the coherency of the growth. The strain in the structures is calculated by comparing the extracted a-lattice parameter to the nominal parameter for an $Al_xGa_{1-x}N$ film with a corresponding AlN mole fraction. $Al_xGa_{1-x}N$ films grown on both AlN and GaN buffer layers are investigated and the impact on the strain formation will be discussed. [1] M. E. Hawkridge et al. Appl. Phys. Lett. 94, 071905 (2009). [2] P.K. Kandaswamy et al. J. Appl. Phys. 106, 013526 (2009).[3] V.N. Jmerik et al. J. Cryst. Growth 311, 2080 (2009).

Session U: Graphene and Nanotubes - Devices

Thursday PM   Room: 102
June 24, 2010   Location: University of Notre Dame

Session Chairs: Huili Grace Xing, Univ of Notre Dame; Debdeep Jena, Univ of Notre Dame

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1:30 PM Student

U1, Sub-20 nm Patterning of Graphene Nanoconstrictions Using Nanosphere Lithography and Characterization of Its Electronic Properties: *Nathaniel Safron*[1]; Michael Arnold[1]; [1]University of Wisconsin-Madison

Graphene has accumulated scientific and technological interest due to its unique physics and exceptional electronic properties. The mobility of carriers in pristine graphene exceeds any known material at room temperature, which, coupled with its extremely high thermal coefficient and current density, make it a suitable candidate material for future electronics. However, due to its semi-metallic band structure, the measured ON/OFF ratios of pristine graphene are limited to ~30, even at low temperature. Experimental work has shown that lateral confinement of graphene to sub-20nm dimensions in graphene nanoribbons can induce higher switching ratios by patterning with E-beam lithography or the unzipping of carbon nanotubes. We have recently demonstrated a self-assembly technique to pattern nanoperforated graphene, where a periodic array of holes are etched into a graphene sheet. The resulting graphene material is a 2D-honeycomb, which has sub-20nm nanoconstrictions between the holes. To achieve this patterning resolution, we have implemented a well-studied self-assembly technique, Nanosphere Lithography, and tailored the process conditions to produce a high-fidelity pattern over entire substrates. Briefly, polystyrene nanospheres are self-assembled into a close-packed hexagonal monolayer through surface-tension effects during controlled drying. Using the nanosphere template, we deposit an aluminum oxide precursor via spin-coating which fills the interstices between the spheres in the template. After oxidation of the alumina precursor, the spheres are removed by chemical solvent leaving an oxide honeycomb pattern defined over the substrate. Utilizing a directional reactive ion etch, we can transfer the pattern to the underlying graphene, creating a honeycomb pattern in graphene. By controlling the etching conditions, we have demonstrated control of the transferred nanoconstriction width from 17 - 7 nm. To test the effect of nanopatterning on the electronic properties of graphene, we have fabricated four-wire field-effect devices of pristine, mechanically-exfoliated graphene, and monitored the effect of each processing step. We have demonstrated that the room-temperature switching ratio of the nanostructured graphene varies inversely with constriction width with ON/OFF ratios of up to 450 for the smallest constriction widths of w = 7 nm with field-effect mobilities of ~1 cm2/Vs. We have observed that the minimum conductance of the nanoperforated graphene follows an Arrhenius behavior with temperature, similar to what would be expected for a small-band gap semiconductor. We have determined the effective transport gap of nanoperforated graphene with constriction widths of w=15 nm to be 54 meV. We attribute the enhanced switching ratio of nanopatterned graphene both to the opening of a band gap and due to Coulomb blockade effects, which have been characterized at low temperature. Additionally, our patterning technique enables large-scale construction of 2D arrays of grapheme nanoconstrictions into designed device structures, enabling a multitude of new experimental measurements.

1:50 PM Student

U2, Carrier Transport in Graphene P-N Junctions: *Tian Fang*[1]; Kristof Tahy[1]; Aniruddha Konar[1]; Huili Xing[1]; Debdeep Jena[1]; [1]University of Notre Dame

High carrier mobility and perfect two-dimensional (2D) structure make graphene a promising material for applications in high speed electronic devices. P-N junctions can enable a number of electronic devices, such as tunneling field effect transistors (TFET). Graphene P-N junctions have been realized experimentally by exploiting electrostatic doping. In this work we present theoretical calculation of I-V curves of graphene p-n junction and the corresponding experimental measurements. Graphene is a zero bandgap material. However, in a graphene p-n junction carriers have to tunneling through an effective bandgap formed by the requirement of lateral momentum conservation. In the calculations we assume the electron transport across p-n junction is ballistic. The p-n junction currents include tunneling and thermal emission current. In a forward biased p-n junction, the electrons with low energy can tunnel through the junction and higher energy electrons can go to drain directly by thermal emission. At high bias the thermal current will be dominant. In a reversed biased p-n junction the tunneling current is dominant. Here, we ignore other recombination processes, such as Auger recombination, in the middle of a forward biased p-n junction. We assume the doping electrodes have good electrostatic control of the carriers in the channel, so that the p-n junction is short enough for ballistic transport. In the diffusive transport regime, we have to include other recombination processes. I-V curve calculations show the reverse biased current is dominantly by the tunneling component thus then does not depend on temperature. The forward biased p-n junction has a thermal emission component so the I-V curves show clear temperature dependence at high bias condition. Graphene p-n junctions were achieved by electrostatic doping in our lab. A 30nm wide raphene channel is deposited on a 300nm thick SiO2 substrate. The carrier density in the channel can be modulated by the back gate voltage

along the channel from source to drain. Half of the channel is covered by a top gate. The top gate dielectric is 15nm thick Al2O3 which is deposited by ALD. The carrier density in the channel under the top gate is controlled by both top and back gates. By changing the voltages of the two gates, the channel can be set to p-p, n-n, n-p or p-n dopings. The conductance measurement shows the p-n and n-p channels show comparable conductance to n-n and p-p channels. In conclusion, we have experimentally achieved graphene p-n junctions using a back and a top gate by electrostatic doping. The I-V curves of p-n junctions are calculated theoretically, and are compared with the experimental data.

2:10 PM

U3, Epitaxial Graphene Materials Integration: Effects of Dielectric Overlayers on Structural and Electronic Properties: *Joshua Robinson*[1]; Michael LaBella[1]; Kathleen Trumbull[1]; Xiaojun Weng[1]; Randall Cavalero[1]; Tad Daniels[1]; Zachary Hughes[1]; Matthew Hollander[1]; Mark Fanton[1]; David Snyder[1]; [1]Penn State University EO Center

The realization of a graphene-based electronic technology necessitates large-area graphene production, as well as the ability to integrate graphene with highly insulating films that act as the gate dielectric in field effect transistors (FETs). The use of high-k dielectric materials in graphene-based FETs is also of interest because of the reduced coulombic scattering of charge carriers, and enhanced charge carrier mobility. Although the use of high-k dielectric materials may limit graphene mobility through phonon scattering, graphene FETs fabricated with high-k dielectric materials still outperform those utilizing SiO2. Atomic layer deposition (ALD) provides a means to produce high quality films for gate dielectrics at temperatures below 300C, and has proven to be an excellent technique toward the integration of dielectrics with graphene. However, because ALD is a water-based technique, graphene must undergo surface preparation processes that will permit the deposition of a uniform dielectric film. Previous reports suggest that functionalization of graphene via ozone, nitrogen dioxide, or perylene tetracarboxylic acid (PTCA) prior to ALD of Al2O3 can result in more uniform dielectric film coverage on graphene, with fewer examples of uniform deposition on pristine graphene. Additionally, successful integration of Al2O3 and HfO2 has been accomplished by depositing a thin (2 – 5 nm) metallic Al or Hf film via physical vapor deposition, which fully oxidized when exposed to atmosphere, and served as a uniform nucleation layer for subsequent ALD processing. We present a means to integrate the high-k dielectric materials Al2O3, HfO2, Ta2O5, and TiO2 with epitaxial graphene, compare surface pretreatments, and provide electronic and structural characterization of the dielectric materials on graphene. We present evidence that, uniform coverage of ALD dielectric films on epitaxial graphene is possible through the use of a nucleation layer and optimization of deposition temperature. Additionally, deposition of dielectric materials via ALD impacts the structural and electronic quality of epitaxial graphene. In some cases, atomic layer deposition of high-k dielectrics can improve the mobility of epitaxial graphene by up to 22%, however, most situations result in mobility degradation. The deposition of Al2O3, HfO2, and TiO2 are shown to introduce minimal degradation to the epitaxial graphene structural properties, while Ta2O5 can significantly degrade the graphene structural quality. Finally, we discuss the use of multilayer films that provide uniform coverage and minimal degradation of epitaxial graphene's electronic and structural properties.

2:30 PM

U4, Comparison of Ballistic Performance of Graphene and Planar III-V MOSFETs for RF Low Voltage Applications: *Lingquan (Dennis) Wang*[1]; Vincent Lee[2]; Francisco Lopez[2]; Yuan Taur[2]; Jeong Moon[3]; Peter Asbeck[2]; [1]University of California, San Diego/Global Foundries; [2]University of California, San Diego; [3]Hughes Research Laboratories

Graphene is under study as a MOSFET channel material due to its high carrier velocities, ~10_8cm/sec for electrons and holes. The high carrier velocities even at low kinetic energies are favorable for low operational voltages. Narrow bandgap III-V materials (InSb, InAs and InGaAs, also with peak electron velocities ~10_8cm/sec) are also candidates for high frequency operation at low bias. In this work, we compare the theoretical performance of graphene and narrow bandgap III-V MOSFETs. Our analysis is carried out for the ballistic transport limit, since future high performance devices will likely have gate lengths near or below the carrier mean free path. Our analysis explicitly accounts for the nonparabolic conduction band in III-V's. Our results show that graphene is expected to exhibit superior on-current and transconductance. The device performance is examined from three perspectives: average carrier injection velocity v$_{inj}$ at the virtual source; sheet charge density (Ns) at the virtual source; and ballistic current. Average velocity: For graphene, v$_{inj}$ remains constant at 2vd/p (~6x107 cm/s), regardless of Ns (vd Dirac velocity). For III-V materials, vinj for low carrier densities is determined by (2kT/pm*)1/2 (InSb: 4.6x107 cm/s, In0.47Ga0.53As: 2.7x107cm/sec) and increases with Vgs as the carrier population reaches degeneracy. Due to strong non-parabolicity in III-V's, vinj depends on channel thickness, and gradually saturates at high Ns, becoming comparable to vinj in graphene. The critical value of Vgs where vinj saturates depends on oxide capacitance, and is near Vgs-Vt=0.5 V for InSb at equivalent oxide thickness (EOT) of 1 nm. Ns at the virtual source: For graphene transistors, charge is confined within the graphene layer, avoiding gate capacitance degradation due to finite centroid depth of the electron wavefunction as occurs in III-Vs. The graphene density of states capacitance also benefits from 2x Dirac point degeneracy. Sheet charge density in graphene transistors consists of both electron and holes. Although the overall Ns at the virtual source remains constant as Vds varies, sheet electron and hole densities individually change. Higher Vds results in more holes at the virtual source. For charge balance, more electrons must be present, leading to increasing electron density with increasing Vds. For unipolar devices, however, holes are absent; since increasing Vds discourages backward going electrons, electron density decreases with increasing Vds. Ballistic Current: Combination of large Ns and high vinj at all Ns levels leads to higher drain current for graphene. For representative 1nm EOT case, the ballistic current (transconductance) for a graphene transistor is 1.8mA/m (4.3mS/m), compared to 0.44mA/m (1.9mS/m) for In0.47Ga0.53As, 0.48mA/m (2.1mS/m) for InAs and 0.45mA/m (1.9mS/m) for InSb (Vgs-Vt=Vds=0.3V). However, given ambipolar conduction within graphene transistors, devices may not turn off at low gate bias. Circuit design thus must accommodate a limited ON/OFF current ratio.

2:50 PM

U5, Graphene Fundamental Trade-offs and Asymmetric Bandgap Opening: *Frank Tseng*[1]; Avik Ghosh[1]; [1]University of Virginia

Graphene's tunable energy bandgap has raised considerations as a future candidate for logic devices, although its small band-gap limits its ON-OFF ratio to only around 50, inadequate for digital logic. Regardless of the limited success using current lithographic techniques there is still research interest in extending graphene's bandgap. However, extension of the graphene bandgap comes at a *fundamental cost to mobility* due to an asymptotic constraint on its short wavelength bandstructure. In evaluating materials for future electronic devices it is useful to analyze and compare fundamental material trade-offs using a *three-parameter analysis* of bandgap, mean-free-path and mobility (Eg-λ-μ). From our three-parameter (Eg-λ-μ) we find that for graphene samples where λ<100nm, graphene actually performs worse in terms of electron mobility compared to some III-V semiconductors such as Indium Antimonide (InSb) and Gallium Arsenide (GaAs) with corresponding bandgaps. Fundamentally, extending the bandgap decreases the low-energy curvature and increases the effective mass, as at higher-k the dispersion is asymptotically pinned to its original linear form. We show a way to quantify this fundamental trade-off for all graphitic materials including, monolayer and bilayer graphene, carbon nanotubes, and strained graphene nanoribbons. Recent experiments have also shown 'kinks' in the IV-characteristics due to band-to-band tunneling, as well as current 'saturation' even for zero bandgap graphene. We point out that a linearly decreasing density in 2D-bulk graphene creates only an inflection in the IV as a graphene device inverts its conduction mechanism. Indeed, only a bandgap can create a plateau in the ballistic graphene IV, long enough for current to be truly considered independent of voltage (current-saturation). Scattering mechanisms inherent to graphene or from interfacing materials can add extra degrees of complexity to understanding properties of graphene-based devices. Using a non-equilibrium green's function (NEGF) formalism for transport and self-consistent Born Approximation to model the affect of phonons, we find that graphene's inherent acoustic phonons lower its mobility. Recent results showing asymmetry

between N and P-type conduction in 2D-bulk graphene can be attributed to an asymmetric bandgap opening relative to the Fermi energy; consequently, the electron and hole effective masses are different. From an asymmetric IV we can extract useful parameters such as mobility from the IV slope and bandgap from the voltage width of current plateau and contact capacitances. In addition, the N-to-P type current saturation ratios and the three-parameter (Eg-λ-μ) analysis together are useful in determining λ and providing a quantitative illustration of the asymmetric bandgap opening.

3:10 PM Break

3:30 PM

U6, Hall Effect Mobility of Epitaxial Graphene on Si-Face SiC: *Shin Mou*[1]; John Boeckl[1]; Jeongho Park[1]; Kurt Eyink[1]; David Tomich[1]; John Hoelscher[2]; Lawrence Grazulis[3]; Steve Smith[3]; Weijie Lu[4]; William Mitchel[1]; [1]Air Force Research Laboratory; [2]Wright State University; [3]University of Dayton Research Institute; [4]Fisk University

Graphene has recently attracted a lot of interest as a promising material for next-generation electronic devices such as digital switches and radio-frequency transistors. A key material parameter driving the interest in this material is the Hall mobility and 300 K mobilities greater than 10,000 cm2/Vs have been reported. However, there are only a few studies relating the Hall mobility to carrier densities and other material properties in a systematic way. Therefore, in this study, we report Hall mobility as a function of carrier densities under different growth conditions. Epitaxial graphene films were grown on 10x10 mm^2 samples diced from CMP polished (0001) semi-insulating on-axis SiC wafers. Ultra high vacuum (~ 1E-10 Torr base pressure) and Argon atmospheric pressure sublimation processes were used over a range of growth temperatures and times. Hall mobilities were measured on both bulk samples (10x10 mm^2 and 4x4 mm^2) and small van der Pauw (vdP) crosses of various sizes (width from 2 μm to 250 μm). The values of mobility obtained are within the range of 100 – 500 cm2/Vs. The general trend is that a higher mobility often correlates to a lower carrier density. Raman spectroscopy and X-ray photoemission spectroscopy were used to confirm the presence of graphene. Atomic force microscope was used to characterize the surface morphology and also transmission electron microscope was used to confirm the number of layers of graphene films. The correlation between mobility, growth condition, and morphology are described in order to relate the growth conditions to the values of Hall mobility. The variation within small vdP crosses and the size dependency are also studied. Generally, there are local variations across the wafer but the median mobility values are consistent with those of the bulk measurement from the same 10-10 mm2 sample. Raman mapping, AFM, and XPS measurements are done on local small vdP crosses to find the correlation between local morphologies and Hall mobilities. Generally, higher Hall mobility value often correlates to better uniformity in terms of the morphology. Thus, for the expitaxial graphene grown on (0001) SiC face growth conditions that give smoother morphology and also lower carrier concentration at the same time are needed to optimize the mobility.

3:50 PM Student

U7, Highly Efficient Photovoltaic Devices with Transparent Graphene Electrode and TiOX Layer: *Minhyeok Choe*[1]; Byoung Hoon Lee[1]; Gunho Jo[1]; June Park[2]; Woojin Park[1]; Sangchul Lee[1]; Woong-Ki Hong[1]; Maeng-Je Seong[2]; Yung Ho Kahng[1]; Kwanghee Lee[1]; Takhee Lee[1]; [1]Gwangju Institute of Science and Technology; [2]Chung-Ang University

Graphene, an ultra-thin two-dimensional sheet of covalently bonded carbon atoms, has been attracting great attention in the field of optoelectronics of organic and inorranic materials. This is because of its outstanding electronic, optical, and mechanical properties, such as quantum electronic transport properties, transparency, mechanical and chemical stability, stretchability, and flexibility. Recently, graphene-based thin films have attracted tremendous attention as a noble transparent electrode material because they are chemically and mechanically robust, electrically conductive, and optically transparent. Our focus is on the application of graphene films as transparent electrodes for organic photovoltaic cells. We present the synthesis of multi-layer graphene (MLG) films by chemical vapor deposition (CVD) and their applications to organic photovoltaic cells. Our MLG films possessed sheet resistances of ~606

/□ at transmittances of ~87% and showed good performance as electrodes for organic photovoltaic cells. Furthermore, cell structure optimization with an inserted TiOX layer enhanced the observed power conversion efficiency up to 3.63% which is the highest efficiency reported for photovoltaic cells with graphene-based electrodes to date.

4:10 PM Student

U8, Integrated Circuits Based on Carbon-Nanotube Transistors and Amorphous-Carbon Thin-Film Load Resistors: *Hyeyeon Ryu*[1]; Daniel Kaelblein[1]; Frederik Ante[1]; Ute Zschieschang[1]; Oliver Schmidt[2]; Hagen Klauk[1]; [1]Max Planck Institute for Solid State Research; [2]Chemnitz University of Technology

Integrated circuits based on carbon-nanotube transistors are potentially useful for electronics on unconventional substrates. From a circuit-design perspective, complementary circuits are preferred, but are difficult to realize, since carbon nanotubes typically only show p-channel behavior. Unipolar circuits require load devices that must have a large resistance to provide gain above unity. In thin-film circuits, load devices are often realized with transistors biased in saturation and having a large length/width ratio. But the resistance of carbon nanotube devices is not a simple function of the length, and the output swing of saturated-load inverters is diminished by the threshold voltage of the load. As an alternative to transistor-based load devices we have developed a low-temperature process to fabricate thin film resistors with linear characteristics and resistances that are easily tuned to provide large gain. We demonstrate the integration of nanotube transistors and thin-film resistors into circuits with full output swing and integrated level-shifting to account for positive threshold voltages. The transistors have aluminum gates patterned by electron beam lithography. The gate dielectric is composed of 3.6 nm thick AlOx (obtained by plasma oxidation) and a 2.1 nm thick organic monolayer (prepared from solution). The carbon nanotubes are deposited from a liquid suspension. Using AFM, an individual nanotube is located on each gate, and AuPd source/drain contacts are defined by e-beam lithography. The best transistors we have obtained have a transconductance of 6 μS, an on/off ratio of 10^7, and a subthreshold slope of 100 mV/decade. Based on the gate capacitance (50 fF) and the transconductance, a cutoff frequency of 20 MHz is projected for these transistors. Load resistors are fabricated by depositing a thin layer of amorphous carbon by RF sputtering and lithographic patterning. Depending on the film thickness, the sheet resistance is between 10^6 and 10^7 Ω/sq. Depending on the geometry, resistances between 10^5 and 10^8 Ω can be designed. Integrated circuits are completed by connecting transistors and resistors with metal interconnects defined by e-beam lithography. Inverters composed of a carbon-nanotube transistor and a carbon load resistor have full output swing, small-signal gain up to 10, and switching frequencies up to 2 MHz.Since our transistors have positive threshold voltages (~0.3 V), the input and output levels of the inverters do not match (the input requires a positive signal to turn the transistor off, but the output produces only negative signals). Therefore, these inverters cannot be cascaded. To realize circuits with matching input and output levels, a level-shift stage composed of two carbon resistors is integrated with each inverter. The level-shift stage translates each input signal towards more positive values and thus allows the inverter to work properly without positive input signals.

4:30 PM

U9, Late News

4:50 PM

U10, Late News

Session V: Quantum Dots, Boxes, and Wires

Thursday PM   Room: 126
June 24, 2010   Location: University of Notre Dame

Session Chairs: James Merz, University of Notre Dame; Diana Huffaker, University of California, Los Angeles

1:30 PM

V1, Toward Conversion from Electron Pairs to Photon Pairs in Quantum Dots: *Ikuo Suemune*[1]; Yasuhiro Idutsu[1]; Makoto Takada[1]; Hirotaka Sasakura[1]; Hidekazu Kumano[1]; [1]Hokkaido University

Quantum information communication and processing are expected to form next-generation highly secure quantum-information networks (QIN). Single photons generated from semiconductor quantum dots (QDs) are expected to play as messenger qubits in QIN. Especially generation of quantum-entangled photon pairs (QEPP) is regarded to be an important key issue to further extend QIN and it has been actively studied to realize on-demand QEPP sources with QDs. Biexciton-exciton cascade photon-pair emission is the major scheme to pursue this direction. But fine-structure splitting (FSS) of exciton states is the widely recognized difficult problem at present. Also it is difficult to realize simultaneous QEPP generation based on spontaneous emissions in QDs in such a manner as the parametric down conversion of an external laser excitation source. In this paper, new possibility of generating QEPP simultaneously with spontaneous emissions in QDs is discussed. Biexciton(XX) and exciton(X) states in a QD generally have different binding energies due to the Coulomb attractive and repulsive forces among the electrons and holes. This results in different oscillator strengths of XX and X and leads to the sequential single photon spontaneous emissions. This is an intrinsic property and seems to be difficult to change. However, this situation can be changed by introducing an additional attractive force between electron pairs [1, 2]. It is well-known that electrons form Cooper pairs below critical temperature via phonon-assisted attractive force between electrons. Recently inter-band radiative recombination processes of electrons and holes in semiconductors were analyzed including the effect of the Cooper-pair formation (the proximity effect) based on second-order perturbation theory[3]. This analysis shows that pairing of spin-singlet electrons drastically enhances the radiative recombination with a pair of holes. Such a drastic enhancement of electroluminescence (EL) has been observed from light emitting diode (LED) with niobium superconducting electrodes [4]. This theory suggests the QEPP generation in this device. These theoretical and experimental results show the possibility of new-type of radiative recombination processes in semiconductors. However for the control of the number state of generated QEPP, inclusion of QDs in the radiative recombination process is essential [2]. The basic requirements to achieve this scheme and the QD-related experiments demonstrating Cooper-pair-based recombination are discussed. For the confirmation of the generated QEPP with high fidelity, it is also required that the generated QEPP are efficiently extracted to the outer optical transmission systems. Some trials towards this direction is also discussed. [1]E. Hanamura, Phys. Stat. Solid. (b) 234, 166 (2002). [2]I. Suemune et. al., Jpn. J. Appl. Phys. 45, 9264 (2006). [3]Y. Asano etal, Phys. Rev. Lett. 103, 187001 (2009). [4]Y. Hayashi etal Appl. Phys. Express 1, 011701 (2008).

1:50 PM

V2, Tensile-Strained Self-Assembled III-V Nanostructures: *Paul Simmonds*[1]; Minjoo Lee[1]; [1]Yale University

We report the first self–assembled growth of dislocation-free, highly uniform, *tensile-strained* III-V nanostructures on a (110) surface. Devices fabricated on the (110) plane of III-V semiconductors could have several advantages over their (001) surface counterparts. Due to suppression of the in-plane Dresselhaus field,[1] carrier spin-lifetimes in (110)-oriented quantum wells can be significantly longer than in equivalent (001)-oriented structures.[2] Additionally, spin-lifetimes can be lengthened by carrier confinement within self-assembled quantum dots (SAQDs).[3] Incorporating the attractive properties of (110) surfaces with

SAQDs is expected therefore to lead to novel devices with potentially very long spin-lifetimes. Long spin-lifetime is a fundamental requirement for many spintronic applications. Driven by compressive strain, SAQDs are readily formed in the well-established InAs/GaAs(001) and Ge/Si(001) systems. In contrast, deposition of compressive materials on other low-index surfaces such as (110) typically results in heavily dislocated two-dimensional films.[4] Achieving the combination of SAQDs with a (110) surface has thus been highly challenging. However, analyses of dislocation energetics and kinetics indicate that the strain relaxation behavior of (001)-oriented material can be replicated on (110) surfaces provided the *direction of strain* is inverted.[5] As such, by analogy to compressively strained SAQDs on (001) surfaces, sufficient *biaxial tension* could result in the self-assembly of dislocation-free nanostructures on (110)-oriented material. To establish the validity of this prediction, we used molecular beam epitaxy to deposit tensile-strained GaP on GaAs(110) surfaces. We discovered that GaP spontaneously forms three-dimensional nanostructures at terrace edges on the GaAs surface. Straightforward control of nanostructure size is demonstrated without the bimodality encountered in (001) SAQDs. The nanostructures exhibit high shape and size uniformity, with smaller dots showing no evidence of dislocations in cross-sectional transmission electron microscopy. Tuning of the growth parameters enables control of nanostructure density. No wetting-layer is observed prior to dot formation, which implies a Volmer-Weber growth-mode for the GaP nanostructures. This study represents a proof of concept for self-assembled growth driven by tensile strain on a (110) surface. It is anticipated that this will form the first step towards a more general description of epitaxial nanostructure self-assembly. [1] V. Sih et al., *Nat Phys* 1, 31 (2005). [2] G.M. Müller et al., *Phys. Rev. Lett.* 101, 206601 (2008). [3] L.M. Woods et al., *Phys. Rev. B* 66, 161318 (2002). [4] B.A. Joyce and D.D. Vvedensky, *Mat. Sci. & Eng. R* 46, 127 (2004). [5] E.P. Kvam and R. Hull, *J. Appl. Phys.* 73, 7407 (1993).

2:10 PM Student

V3, Self-Assembled In$_{0.5}$Ga$_{0.5}$As Quantum Dots on GaP(001): *Yuncheng Song*[1]; Paul Simmonds[1]; Minjoo Lee[1]; [1]Yale University

We demonstrate growth of In$_{0.5}$Ga$_{0.5}$As self-assembled quantum dots (SAQDs) on GaP as a step towards the integration of efficient optoelectronic III-V materials with Si. Although high-quality GaP has been grown on Si, [1-3] its indirect bandgap makes it unsuitable for most photonic applications. Use of dilute-nitride and boron-containing alloys to achieve a direct bandgap on GaP/Si have yielded promising results, [1, 2] but these complex alloys are not fully understood. GaAsP or InGaP buffers can be grown on GaP/Si to attain a direct bandgap, but the additional thickness resulting from grading can cause problems due to thermal expansion mismatch. To avoid these issues, our approach to obtaining light emission on GaP was to start with the well-established In$_x$Ga$_{1-x}$As material system. In$_x$Ga$_{1-x}$As on GaP offers both a direct bandgap and suitable carrier confinement. However, the lattice mismatch between In$_x$Ga$_{1-x}$As and GaP is too large (4-10%) to permit growth of high-quality quantum wells. Instead, we proposed that this high strain could result in the formation of In$_x$Ga$_{1-x}$As SAQDs, thus providing a relatively simple route to achieving light emission on GaP. We used MBE to deposit various thicknesses of In$_{0.5}$Ga$_{0.5}$As on GaP(001). Streaky 2x4 RHEED patterns during homoepitaxy at 590°C indicated that the GaP buffers were smooth, and an RMS roughness of 0.81nm over an area of (10μm)^2 was measured by AFM. After GaP buffer growth, samples were cooled to 490°C and In$_{0.5}$Ga$_{0.5}$As was deposited at 0.2ML/s with V/III ratio ~40. After an initial wetting layer of ~1.1ML, the RHEED pattern changed from streaky to spotty, indicative of the Stranski-Krastanov (S-K) growth mode. The In$_{0.5}$Ga$_{0.5}$As/GaP QD densities ranged from 2-7x10^{10} cm^{-2} as In$_{0.5}$Ga$_{0.5}$As coverage was increased from 1.23–1.95ML, similar to the dot densities in the well-known InAs/GaAs (001) system. [4] Over this In$_{0.5}$Ga$_{0.5}$As thickness range, average dot size remained constant, to within error, at ~17 nm in diameter and ~2.5 nm in height. Based upon the common cation and common anion rules, In$_{0.5}$Ga$_{0.5}$As SAQDs on GaP are expected to provide effective confinement for both electrons and holes. Further optical and structural characterization will be presented. This work demonstrates the ability to grow In$_{0.5}$Ga$_{0.5}$As SAQDs on GaP(001) via the S-K mechanism. We believe that these results are the starting point for a promising new approach to III-V optoelectronic device integration on Si. [1] B.

Kunert, et al, phys. stat. sol. (b) 244, 2730–2739 (2007) [2] H. Yonezu, et al, J. Cryst. Growth, 310, 4757–4762 (2008) [3] T. Grassman et al, Appl. Phys. Lett, 94, 232106 (2009) [4] D. Leonard et al, Phys.Rev. B 50, 11687–11692 (1994)

2:30 PM Student
V4, Time-Resolved Spectroscopy of Single Colloidal CdSe Nanowires with Picosecond Resolution: *Joseph Herzog*[1]; Alexander Mintairov[1]; James Merz[1]; [1]University of Notre Dame

Nanowires (NWs) have the potential to enhance the speed and efficiency of optoelectronic devices; however, there is much unknown about the physics of these colloidal nanowires. Time-resolved (TR) spectroscopy provides useful information about these nanostructures. In the present study we performed TR spectroscopy at low temperatures (~10K) in order to study the emission properties of single colloidal CdSe nanowires (NWs) with diameter ~20 nm. A streak camera with resolution up to 8 picoseconds (pulse width) was used with a micro photoluminescence (µPL) setup to achieve micron spatial resolution measurements on several individual nanowires. We excited the NW samples with the second harmonic of a Ti-sapphire laser (wavelength at 400 nm, pulse frequency of 76 MHz) with a power density reaching the sample that can range from 100 W/cm2 to 25 kW/cm2. We also measured µPL spectra with an 80x, NA = 0.75 micro objective using the pulsed laser. Wide field luminescent images taken with the micro-objective verified that individual nanowires are measured. Low temperature TR spectroscopy of single nanowires shows a red-shift as a function of time which increases with power. At the largest pump powers (25kW/cm2) the spectra peak shifts ~20 meV within 500 psec. The shift is reduced but observable at lower pump powers, e.g., 1.4 meV in 500 psec for 200 W/cm2. In addition to the peak energy shift, the spectra half-width also decreases with time and pump power. At large pump powers the spectra emission range (FWHM) decreases ~40 meV in 500 psec.   The peak energy shift as a function of time suggests that excitons populate many discrete localized states ranging in energy. At low temperature excitons are prevented tunneling to lower states before they recombine [1]. We believe that these states come from traps in the nanowire. The larger power densities create more excitons that fill more traps of various energy levels; this causes the largest energy shift in the emission. Work was supported by the National Science Foundation, NSF-NIRT grant No. ECS-06 09249. We are greatful to, Dr. M. Kuno, Chemistry Department, University of Notre Dame, for the NW samples. [1] J.J. Glennon, R. Tang, W. E. Buhro, and R. A. Loomis. Phys. Rev. B 80 081303(R) 2009.

2:50 PM
V5, Late News

3:10 PM Break

3:30 PM
V6, Resonant Periodic Gain InAs Quantum Dot VECSEL: *Alexander Albrecht*[1]; Christopher Hains[1]; Thomas Rotter[1]; Andreas Stintz[1]; Kevin Malloy[1]; Ganesh Balakrishnan[1]; [1]University of New Mexico

Edge-emitting semiconductor lasers based on MBE-grown, self-assembled InAs quantum dot (QD) active regions emitting around 1300 nm have demonstrated excellent device performance, including low sensitivity to operating temperature and record-low thresholds. The application of QDs in vertical-cavity lasers requires the stacking of several QD layers to achieve sufficient gain for lasing. The resulting accumulation of strain can affect material quality and degrade device performance. In this investigation we compared two different arrangements of the QD active regions in a vertical-external-cavity surface-emitting laser (VECSEL) structure, both utilizing a total of 12 InAs QD layers, each embedded inside an InGaAs quantum well. The first, a more traditional VECSEL design consists of groups of 3 closely spaced QD layers placed at 4 adjacent antinodes of the optical standing wave. The second structure employs a purely resonant periodic gain (RPG) structure, with each of the 12 QD layers placed at a separate electrical field antinode. This design allows for greater spacing between the InAs layers, greatly reducing the negative effects of strain accumulation. The devices were mounted to a thermo-electrically cooled stage using thermal grease. A fiber-coupled 808 nm diode laser was used as pump source, focused to a 300 µm diameter spot on the semiconductor surface.

A 1% transmission output coupler with 25 cm radius of curvature completed the VECSEL cavity. CW operation was achieved with thermally limited output powers of 400 mW for the RPG structure, compared to only 100 mW for the traditional design. Making use of the growth non-uniformity across the 3 inch GaAs substrate, the operating wavelength could be tuned from 1220 nm to 1280 nm.A portion of the RPG sample was thinned by mechanical polishing to 100 µm and the chip was bonded with indium to a thermal grade polycrystalline CVD diamond heat spreader of 300 µm thickness. The resulting assembly was clamped in a water cooled copper heat sink maintained at a temperature of 20°C. This greatly increased the usable pump power before thermal rollover, resulting in 2.5 W of cw output power, the first reported multi-Watt level QD VECSEL around 1250 nm.

3:50 PM
V7, Quantum Dot Light Emitting Devices and Exciton Recombination Zone: *Seonghoon Lee*[1]; [1]Seoul National University

Colloidal quantum dot (QD)-based light-emitting diodes (QLEDs) have the advantageous features of a narrow emission bandwidth, a wide emission spectral window in the visible region, and a low-cost synthesis based on a solution process. For the realisation of full-colour displays and solid-lighting applications with QLEDs, the development of a fabrication process for the deposition of homogeneous and uniform QD layers over a large area with patterning capability is necessary. Here we present QLEDs over a large area via the elaboration of all-QD multilayer films prepared by a layer-by-layer assembly method, which possess excellent device–performance. From the systematic analysis of the exciton-recombination zone within all-QD multilayer films using a sensing QD layer, optimal QD coverage was found to be 1.2 ~ 1.5 monolayers for the best QLED performance. The total EL emission came mostly at the top QD monolayer (~ 90%) and partially at the second QD monolayer from the top. Multi-coloured QLEDs were also demonstrated by controlled arrangement of variously coloured QDs (red, orange, yellow–green, and green) in the exciton-recombination zone. Practical large-area RGB QLED and flexible solid-state white light emitting devices can be produced.

4:10 PM Student
V8, Thermal Stability in Emission Peak in Multilayer InAs/GaAs Quantum Dot Heterostructure in Laser Application: Nilanjan Halder[1]; Sourav Adhikary[1]; *Subhananda Chakrabarti*[1]; [1]IIT Bombay

Self assembled quantum dots (QDs) are of substantial interest in laser device fabrication due to the strong localization of electronic wave function in these systems leading to an atomic-like density of states. Stacked InAs/GaAs QDs are used in the active region of the laser structures, which increases the active volume of the device and permits to realize enhanced modal gain and low threshold current of the devices. The high temperature growth of AlGaAs-cladding layers for the laser structures leads to pronounced blue-shifting of emission from the QDs caused by In/Ga inter-diffusion. This is undesirable for DFB lasers and VCSELs requiring strict tolerances on operating wavelength. We have investigated the annealing of MBE grown InAs/GaAs multilayer (x10) QDs (MQD) with a combination capping layer of InAlGaAs (30Å) and GaAs (180 Å). The capping/barrier thickness in the MQD samples is optimized in order to produce a 10 layer heterostructure having almost structurally correlated islands upto the final (10th) layer. No frequency shift in the peak emission wavelength is seen even for annealing the samples up to 700°C. XTEM images of the stacked QD samples revealed that the QDs are preserved even annealing up to 800°C, while dissolution of the QDs into the surrounding wetting layer occurred at 850°C. To explain the thermal stability in the emission wavelength a single layer QD (SQD) sample with similar combination cap thickness as the multilayer structure was grown. The peak emission wavelength (1162nm) of the MQD sample remains relatively stable at higher annealing temperatures (upto 700°C) than the SQD sample. PL spectrum of the as grown MQD sample contains two peaks separated from each other by 125 meV, indicating that the peaks are due to two different families of dots and with increasing annealing temperature only one single peak at 1162 nm becomes prominent due to redistribution of In adatoms leading to a more uniform dot size density. Suppression of the strain-enhanced intermixing in QD microstructures can be ascribed for the

thermal stability of the PL peak. In both the samples there is very less material intermixing at the periphery of the QDs due to the quaternary alloy cap, which creates a In rich region along the QD periphery thereby preventing the strain enhanced In/Ga inter diffusion. But the material intermixing from the barrier at the QD base still continues in the SQD sample during annealing due to the usual compressive strain at the base of the pyramidal QDs, where as in the MQD sample the intermixing at the base is suppressed due to the overlapping vertical strain from the under lying dot layers in the QD stack which maintains a strain relaxed state at the QD base. Acknowledgment: DST, India.

4:30 PM
V9,   Enhancement of Luminescence Efficiency in InAs/GaAs Quantum Dots by Proton Irradiation: Sreekumar Rajappan Achary[1]; Saumya Sengupta[1]; *Subhananda Chakrabarti*[1]; Shrikrishna Gupta[2]; [1]Indian Institute of Technology Bombay; [2]Bhabha Atomic Research Centre

Quantum dot (QD) based devices are emerging as an alternate platform for quantum well based devices. Low threshold current density and the ability to tune the emission wavelength from 1500 nm to 1100 nm makes InAs/GaAs QDs more attractive for applications in lasers, infrared detectors, focal plane arrays and in telecommunication. Lots of research is being carried out to improve the characteristics of QDs to reach the theoretically expected device efficiency. One of the major characteristics of InAs/GaAs based QDs, that is being worked on is the photoluminescence (PL) efficiency to realise highly efficient low-threshold QD lasers. To improve the PL efficiency in InAs/GaAs QDs, different techniques are such as deuteration, nitrogen treatment on the QDs before capping, stacking of multi-layers of QDs, and QDs grown in dot-in-the-well structure are used. Leon et al. [1] observed a marginal enhancement of PL efficiency in InGaAs/GaAs QDs due to proton irradiation. The present work elucidates a detailed study on the enhancement of PL efficiency induced by proton irradiation in self assembled InAs/GaAs quantum dots grown over GaAs substrate. Protons of energies ranging from 3 MeV to 5 MeV are used to irradiate QDs. The optimum energy (4 MeV) and fluence required to obtain maximum PL efficiency is investigated. X-ray diffraction analysis showed an enhancement in crystalline quality of the GaAs capping layer. Low temperature PL study exhibited a increase of PL efficiency (upto 7-fold) with increase in proton fluence. The enhancement of PL efficiency is attributed to the annealing of structural defects present in the GaAs matrix that act as a non-radiative recombination centres and release of strain between the QDs and the capping layer, induced by proton irradiation. FWHM of the ground state PL emission decreased from 27.77 meV to 21.29 meV on increasing proton fluence. The thermal spike generated (for few tens of pico second duration) during the passage of protons could have helped to anneal the structural defects and promoted greater homogeneity in size distribution. A similar type of observation was reported by Chakrabarti el al. using nano second pulsed laser annealing on InAs/GaAs QDs [2]. The activation energy of the sample irradiated with protons showed a higher value of 365 meV compared to the as-prepared samples (126 meV). The increase in activation energy depicts the increase of quantum confinement in QDs induced by proton irradiation. Thus by proton irradiation one could enhance quantum confinement and PL efficiency of QDs, which would benefit QD resonant microcavity LEDs and VCSELs, that has limited number of QDs in active region. Financial assistance from DST, is being kindly acknowledged. [1] R. Leon et al., Appl. Phys. Lett. 76, 2074 (2000). [2] S. Chakrabarti et al., J. Electron. Mater. 33, L5 (2004).

4:50 PM
V10,   Late News

Session W: Semiconducting and Metallic Nanowires

Thursday PM   Room: 129
June 24, 2010   Location: University of Notre Dame

Session Chairs: David Janes, Purdue University; Xiuling Li, University of Illinois

1:30 PM Student
W1, Single Crystalline Wurtzite GaAs Nanoneedles Epitaxially Grown on Highly Lattice-Mismatched Sapphire with Bright Luminescence: *Wai Son Ko*[1]; Linus Chuang[1]; Michael Moewe[1]; Kar Wei Ng[1]; Shanna Crankshaw[1]; Thai-Truong Tran[1]; Roger Chen[1]; Connie Chang-Hasnain[1]; [1]University of California, Berkeley

Heterogeneous integration of dissimilar single-crystalline materials, such as III-V compound on Si or sapphire, enables functionalities and performance that cannot be achieved with single material system. Yet, lattice mismatch makes growing high quality thin film on dissimilar substrates difficult. Recently high quality nanowires have been demonstrated on substrates with large lattice mismatches [1]. However, in that case, there exists a critical nanowire diameter for a given mismatch, below which single crystalline can be obtained. This, in turn, presents an upper bound of the substrate lattice mismatch to ~15%, on which nanowires with physically meaningful diameters can be attained with the growth of three-dimensional nano-structures. In this paper, we report a completely new growth mechanism that leads to self-assembled, single crystalline GaAs nanoneedles grown on a sapphire substrate with 46% lattice mismatch. The needles exhibit a single crystalline wurzite phase, have a sharp hexagonal pyramid shape and can be scaled to micron size with growth time. The GaAs nanoneedles were grown on a (0001) sapphire substrate in a commercial MOCVD at 400°C. The growth was spontaneous without any prior substrate surface treatment. At typical growth condition, the nanoneedle shows a hexagonal base, six slanted sidewalls and a sharp tip. With one-hour growth time,the nanoneedle has a base diameter of ~600 nm and a height of ~3 μm. Furthermore, high-resolution TEM shows that the tip is ~ 3 nm wide, and the needle has a taper angle of ~11°. TEM and diffraction analysis reveals that the NN has single-crystalline wurtzite structure as opposed to the normal zinc-blende GaAs structure. The effect of growth condition on nanoneedle was studied by varying the growth time. When the growth time was varied, the base dimension and height of the nanoneedle scales linearly, maintaining the same taper angle, even when the growth time was only 1.5 min. This suggests that the nanoneedle nucleates as a seed and grows with a two-dimensional thin-film deposition process on the six sidewall facets. Despite the large 46% lattice mismatch, the NN shows bright photoluminescence. A 514 nm excitation laser is focused down to a ~1.5 μm spot. With 100 μW excitation power, the NN shows emission peak at 1.519 eV at 4 K. The linewidth of the peak is 18 meV. This narrow linewidth indicates the excellent crystal quality of the NN. These high-quality GaAs NNs open an opportunity for integrating high-performance electronic and optoelectronic devices onto highly lattice-mismatched substrates. [1] L. Chuang *et al*, *Appl. Phys. Lett.* 90, 043115 (2007).

1:50 PM
W2, Twinning Superlattice in VLS Grown <110> Planar GaAs Nanowires Induced by Impurity Doping: *Xiuling Li*[1]; Ryan Dowdy[1]; Seth Fortuna[1]; Donald Walko[1]; Jian-Guo Wen[1]; [1]University of Illinois

Self-aligned, twin-free, planar <110> GaAs nanowire growth by metal-organic chemical vapor deposition (MOCVD) through the vapor-liquid-solid (VLS) mechanism has been demonstrated by our group recently (Fortuna, Wen and Li, Nano Letters, 2008). Well-defined transfer and output characteristics with bulk-like mobility have been reported from MESFETs fabricated using these planar nanowires intentionally doped by silicon as the channel materials (Fortuna and Li, IEEE Electron Device Letters, 2009). In this paper, the planar nanowire growth is perturbed by introducing p-type dopants in situ. Twinning superlattice planar nanowires, which could be useful for miniband related

devices, are reported. At doping levels as low as 0.008% Zn/Ga (gas phase ratio), periodic notching along the axis of the nanowire is observed. The notches are confirmed to be <111> twin-plane defects by transmission electron microscopy (TEM), which lead to a <110> planar nanowire superlattice structure with <111> twin-planes. Note that the twin plane superlattice is formed at constant Zn flow without any modulation, and its periodicity corresponds to the nanoparticle catalyst size at a ratio of ~ 0.9. At Zn/Ga gas phase ratio of 0.8% or higher, the nanowire propagate incoherently out-of-plane. There appears to be an incubation period for Zn incorporation and accumulation effect which renders delay in the twinning and causes initially twinned planar nanowires to take off from the plane. In comparison to <111> vertical III-V nanowires, the threshold of impurity level for such structural perturbation is orders of magnitude lower. These observations underscore the atomic nature of the nucleation process in the VLS mechanism, where any perturbation at atomic level such as dopant incorporation can be critical to the free energy of the interface not only between metal catalyst and semiconductor solid surface, but also at the three-phase boundary. In particular, planar nanowires reported here, where this three phase region is not symmetric, can be more easily perturbed to induce structural changes.

2:10 PM Student
W3, Photoluminesence of InGaAs Nano-Pillar Arrays on GaAs Substrate:
Joshua Shapiro[1]; Adam Scofield[1]; Clayton Tu[1]; Diana Huffaker[1]; [1]UCLA

Catalyst free growth of uniform arrays of InGaAs nanopillars with varying indium fraction on gallium-arsenide (111)B substrate by selective area MOCVD is reported. Pillar formation is studied as a function of pillar diameter. Compositional analysis is determined by energy dispersive spectroscopy and confirmed by temperature dependent photo-luminesence(PL). PL emission at 77K from two different samples with indium fractions of 0.24 and 0.48 is intense at 1.1µm and 1.43µm respectively. Faceted pillars with vertical side walls and a flat hexagonal top surface and with diameters from 100nm to 350nm were formed for estimated indium fraction of 0.24. Pillars with diameters < 200nm are well formed for estimated indium compositions of 0.48, however larger diameter begin to coalesce with their neighbors.

2:30 PM Student
W4, Synthesis and Characterization of GaAs/MnAs Core/Shell Nanowires:
Nicholas Dellas[1]; Jing Liang[1]; B.J. Cooley[1]; Dave Rench[1]; Jeremy Cardellino[1]; Nitin Samarth[1]; Suzanne Mohney[1]; [1]Pennsylvania State University

Hybrid semiconductor/ferromagnetic heterostructures are of interest for injection of spin polarized currents into semiconductors for spintronic applications. Here we have synthesized GaAs/MnAs core/shell nanowire (NW) heterostructures by catalyst-free molecular beam epitaxy (MBE). Transmission electron microscopy (TEM) reveals that the GaAs core grows with the zinc-blende crystal structure with a [111] growth direction, and in a small population of wires, the crystal structure transitions from zinc-blende into the wurtzite phase with a [001] growth direction. Cross-sectional TEM shows that the MnAs grows epitaxially in the NiAs prototype structure on zinc-blende GaAs core with an epitaxial relation of [201]MnAs||[111]GaAs and (010)MnAs||GaAs(-110). When the GaAs core is found to be in the wurtzite structure, the epitaxial relation between the GaAs and MnAs changes to [001]MnAs||[001]GaAs and (-120)MnAs||(-120)GaAs. Preliminary magnetic force microscopy measurements of these NWs indicate the presence of ferromagnetic domains at room temperature, consistent with the magnetic properties of bulk MnAs crystals which typically have a Curie temperature of 318 K. This work is supported by NSF under the MRSEC program and the NNIN.

2:50 PM Student
W5,   Contact Laser Annealing Effects on Indium Oxide Nanowire Transistors: *Seongmin Kim*[1]; Sunkook Kim[1]; Chunghun Lee[1]; Pornsak Srisungsitthisunti[1]; Pochiang Chen[2]; Chongwu Zhou[2]; Xianfan Xu[1]; Minghao Qi[1]; Saeed Mohammadi[1]; Sanghyun Ju[3]; David Janes[1]; [1]Purdue University; [2]University of Southern California; [3]Kyonggi University

Wide band-gap oxide nanowires, such as ZnO, SnO_2 and In_2O_3, are attractive candidate for next-generation electronics, because of their high mobilities and compatibility with low temperature processes. Nanowire transistors (NW-FETs) using these materials could provide the drive electronics for future transparent/

flexible displays, based on their optical transparency and mechanical flexibility. Recent studies report several methods to prevent threshold voltage degradation in oxide semiconductor (ZnO and In_2O_3) based-TFT devices. In order to move toward future commercial nano-electronics, it is also necessary to improve and stabilize the transistor characteristics of nanowire devices and to understand the mechanisms responsible for the current-voltage relationships. We have fabricated In_2O_3 NW-FETs using Al and ITO metal contacts, and studied the effects of annealing via femtosecond laser pulses focused on the contact regions. The n-channel NW-FETs utilized single-crystal In2O3 nanowires (d ~ 20 nm) and channel lengths of 1.5-2 microns. In order to investigate the effects of post-metallization S/D annealing, the device electrical characteristics were measured before and after annealing. The Ids-Vds curves of as-fabricated devices deviate significantly from the expected response of a long-channel transistor even at Vds values expected to be in the saturation region, and exhibit significant gds. The annealing induces significant positive shifts in the threshold voltage, a reduced saturation drain voltage and a significantly reduced drain conductance (g_{ds}) in the saturation region, along with modest improvements in the subthreshold slopes. Fully transparent NW-FETs were also fabricated utilizing ITO contacts and glass substrates. After laser annealing the ITO contacts, the threshold voltage is positively shifted, and slight improvements in Ion/Ioff and effective mobility are observed. A small reduction in contact resistance is also observed after annealing. The laser annealing is expected to modify the metal/semiconductor interface, including interface state densities. Also, increased roughness at the contact-nanowire interface after annealing is expected to improve the contact-channel interface, reducing the contact resistance and modifying the Schottky barrier height in the nearby semiconductor region. The low frequency (1/f) noise in single In_2O_3 nanowire transistors was also measured before and after contact laser annealing. The amplitude of the current noise spectrum (S_I) is found to be proportional to I_d^2 in the transistor operating regime. According to the gate dependence of the noise amplitude, the extracted Hooge's constants are ~ 1.11 $\times 10^{-2}$ for as-fabricated devices and ~ 6.47×10^{-3} for laser annealed devices. The reduction of Hooge's constant after laser annealing implies a modification of the interface states and trap centers located in the space charge region. This study provides insights into the contact-dominated transistor properties and reports that laser annealing is a promising optimization technology for the realization of low power transparent/flexible display circuits, in terms of the effects on output conductance and threshold voltage.

3:10 PM Break

3:30 PM Student
W6, Vertical InSb Nanowire Arrays Electrodeposited into Porous Anodic Alumina Templates on Silicon Substrates: *Suprem Das*[1]; Asaduzzaman Mohammad[1]; Yong Chen[1]; Timothy Sands[1]; David Janes[1]; [1]Purdue University

InSb is a III-V direct bandgap semiconductor having zincblende crystal structure, a small bandgap (Eg = 0.17 eV) and the highest carrier mobility (μ_e = 78,000 cm^2 V^{-1} s^{-1}) among all bulk semiconductors at room temperature. InSb nanowires have potential applications ranging from high speed, low power logic applications, thermoelectric power generators, Peltier coolers and infrared detectors. Although the Vapor-Liquid-Solid mechanism is often used to grow the nanowires using CVD or MBE methods, these methods are usually expensive and often associated with a wetting issue of the nanowire sidewalls by gold coming from the gold catalyst droplets. In contrast, solution-grown methods of fabricating the nanowires can be effective and also can be exploited for non-lithographic fabrication of nano-devices. In this work, we have synthesized InSb nanowires within porous anodic alumina (PAA) templates having pores of ~ 20 nm diameter. The PAA template utilizes an evaporated film on a silicon wafer (Si/Ti (100nm)/Al (1.5µm)), with a two-step anodization process using 0.3M H_2SO_4 at a voltage of 20V and a temperature of 40C. Prior to nanowire deposition, the alumina barrier layers were removed from the pore bottoms using a reverse anodization process. A direct current electrodeposition method was used to grow the InSb nanowires into the nanopores at various deposition potentials (reduction potentials of -1.0V to -1.5V). The nanowires were characterized using Field Emission Scanning Electron Microscopy (both cross sectional view and planar view), Transmission Electron Microscopy and Raman

Spectroscopy. The FESEM images show that the nanowires have diameters = 20nm and grow along the pores starting from the pore bottom. The TEM image shows the crystalline quality of the InSb nanowires. The room temperature Raman spectra of the nanowires were taken at different laser powers using λ = 532nm excitation source in a backscattered geometry. We observe both the TO and LO phonon modes of InSb zincblende structure along with second order phonon processes involving 2TA and TO-TA phonon modes. The TO and LO modes were observed at $\upsilon \sim$ 178 cm^{-1} and 194 cm^{-1} respectively and the 2TA and TO-TA modes were observed at $\upsilon \sim$ 105 cm^{-1} and 140 cm^{-1} respectively. Both the Raman Spectroscopy intensities and Raman shifts can be explained on the basis of size effects and carrier confinement in the semiconductor nanowires.

4:10 PM

W8,   Formation of Periodic Nanostructures through Kirkendall Constitutional Interdiffusion in Epitaxial Heterostructures: *Patrick Taylor*[1]; Wendy Sarney[1]; Venkataraman Swaminathan[2]; [1]US Army Research Laboratory; [2]US Army ARDEC

   IV-VI materials are of interest for high-performance infrared detectors because they possess extremely large infrared absorption coefficients. However, these technologies are limited by the lack of suitable epitaxial substrate that is matched in both lattice and thermal expansion coefficients. Those mismatches can have effects that reduce photo-carrier diffusion and degrade infrared detection. ZnTe is an interesting new substrate candidate for this system because it has a very close match in lattice constant (misfit $\sim$ 0.33%), and a reasonable match in thermal expansion. (ZnTe: 8.2 X 10-6/K and PbSe: 19.4 X 10-6/K). Using this approach, PbSe infrared active layers having unusually low dislocation density and high crystallinity have been demonstrated. One interesting phenomenon associated with this approach is the spontaneous formation of regularly spaced hollow nanostructures that are formed at the heteroepitaxial interface. We will present evidence showing that these nanostructures are formed by a Kirkendall diffusion mechanism at the interface between PbSe and ZnTe epitaxial layers. SIMS measurements are consistent with a chemical exchange reaction driven by the relatively more rapid diffusion of zinc into the PbSe layer leaving a semi-regular array of hollow nanostructures at the interface. For PbSe epitaxy onto ZnTe, the center-to-center spacing of misfit dislocations would be 96 nm. Using HRTEM, the nanostructures appear to be hollow nanotubes that have a distributed spacing centered between 100-150 nm, which is consistent with the linear equilibrium spacing of misfit dislocations. This consistency suggests that the nanostructures nucleate at the highly strained locations of the interfacial misfit dislocations. HRTEM measurements also show that the formation of the nanostructures is accompanied by the preferential formation of ZnSe and related PbZnSe solid-solution alloys.

4:30 PM Student

W9,   Thermal Conductivity of Aluminum Nanowires near Room Temperature: Direct Measurements and Theory: *Nenad Stojanovic*[1]; Sanjeeva Maithripala[1]; Jordan Berg[1]; Mark Holtz[1]; [1]Texas Tech University

      Electrical and thermal conductivity are important fundamental material quantities to establish for understanding and predicting device properties when nanoscale dimensions are involved. Obtaining direct results for electrical resistivity is readily achieved. However, direct measurements of thermal conductivity is extremely difficult due to fabrication and parasitic heat transport issues. Direct measurements are reported of thermal conductivity for aluminum nanowires. A nanofabricated electrothermal test structure is described for studying the nanowires near room temperature. Nanowires studied are 100 nm thick with 75, 100, and 150 nm widths. The thermal conductivity is found to be substantially lower than for bulk Al, and to decrease as nanowire width is reduced. Measurements of the electrical resistivity show it to increase with reduced nanowire width. These combined measurements allow examination of the Wiedemann-Franz law and to investigate the importance of phonon heat propagation in metals at room temperature.To aide in the interpretation of the results, we develop an approach for calculating the electron and phonon thermal conductivities, as well as the electrical conductivity. Effects such as surface and grain boundary scattering, which are negligible for larger structures, significantly influence electrical and thermal properties of nanoscale objects. The

conventional wisdom for metals holds that thermal transport is predominantly by electrons, and that contribution due to lattice vibrations—that is, thermal transport by phonons—is negligible. Furthermore, it is usually assumed that transport by electrons is identical for describing current and heat. These assumptions are often used to justify the use of the Wiedemann-Franz law to infer thermal conductivity based on measurements of electrical resistivity. Our experiments suggest a breakdown of the Wiedemann-Franz law at the nanoscale. Solution of the Boltzmann transport equation for both electrons and phonons in nanowires will be used to examine the applicability of Wiedemann-Franz law at the nanoscale. It is found that Wiedemann-Franz law can be used to obtain the electronic component of thermal conductivity to good approximation, but that the phonon term must be considered in order to properly estimate total thermal conductivity of metallic nanowires. The calculations are extended to theoretically treat several other metals at room temperature.

4:50 PM

W10,   Simulation of the Influence of Grain Boundaries on Resistivity via the Wigner-Fokker-Planck Equation: *Richard Sharp*[1]; Katayun Barmak[1]; [1]Carnegie Mellon University

      The resistivity of polycrystalline conductors such as copper increases sharply as the size of a conducting sample approaches the mean free path of the electrons. Models for this phenomenon have been based on surface scattering of electrons (Fuchs and Sondheimer) and on grain boundary scattering (Mayadas and Shatzkes). Recent experimental results from Barmak and collaborators attribute the majority of the effect to grain boundary scattering. Here, we employ a temperature dependent open quantum kinetic model, the Wigner-Fokker-Planck (WFP) equation, to examine the resistivity size effect at the grain boundary level. Temperature dependence and the full quantum nature of the model, allowing nearby grain boundaries to interact in a nonlinear manner, yield a more detailed model than those above or subsequent refinements such as that of Warkusz.The WFP equation models the time evolution of the Wigner function, which is the Wigner transform of the quantum density operator into the phase space of the system. In the model, electrons interact with an electric potential and phonons. The electron-phonon scattering is applied by using a quantum Fokker-Planck operator, effectively a heat bath of harmonic oscillators, adding lattice temperature to the model. The WFP equation is related to Schroedinger's equation, indeed the two are equivalent when electron-phonon scattering is neglected in the WFP equation, and less directly to the Boltzmann equation through its mathematical form and phase space representation of the solution. Our initial simulations consider a one-dimensional model of a copper wire inspired by the situation considered by Mayadas and Shatzkes: a wire in which all grain boundaries are perpendicular to the axis parallel to the current and uniform in this cross section. The grain boundary is introduced as a square potential barrier and added to a linear potential resulting from a constant electric field. A single temperature dependent model parameter, the coupling strength between the system and heat bath, is determined by calibrating the free system (a wire with no grain boundaries) so that it yields the bulk resistivity of copper. The steady state solution of the WFP equation is computed using the discontinuous Galerkin method (as implemented by Gamba, Gualdani, and Sharp), open-system boundary conditions such as those discussed by Frensley, and an applied linear potential to drive a current past the grain boundary. The current density and thus resistivity of the wire are recovered from the steady state Wigner function. The approach, which has been established for the basic situation described here, will allow detailed examination of the grain boundary effect on resistivity.

Technical Program

Session X: Narrow Bandgap Semiconductors: Infared Detectors and Lasers

Thursday PM   Room: 131
June 24, 2010   Location: University of Notre Dame

Session Chairs: L. Ralph Dawson, University of New Mexico; Mark Wistey, University of Notre Dame

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1:30 PM

X1, Minority Carrier Lifetime in LWIR Type II Superlattice Detector Structures Using Time-Resolved Photoluminescence: *Blair Connelly*[1]; Grace Metcalfe[1]; Paul Shen[1]; Kevin Clark[2]; Paul Pinsukanjana[2]; Michael Wraback[1]; [1]U.S. Army Research Laboratory; [2]Intelligent Epitaxy Technology, Inc.

Type II InAs/GaSb superlattice (T2-SL) long wavelength infrared (LWIR) detectors for the 8-12 µm wavelength range are expected to have lower dark current noise than HgCdTe photodetectors due to the suppressed Auger recombination rate that comes from the ability to engineer the band gap. One of the primary limiting factors in the performance of these devices is the minority carrier lifetime, which is directly related to the dark current noise and quantum efficiency. Previous studies have determined the recombination lifetime in LWIR T2-SLs by analyzing the dark current versus voltage and quantum efficiency. These studies rely on modeling, while optical measurements can provide a more direct measurement. However, there has been no reported optical measurement of the minority carrier lifetime in these devices. We present a direct optical measurement of the minority carrier lifetime. These optical measurements help determine the mechanisms that limit the performance of LWIR detectors and guide growth techniques to improve device performance. Time-resolved photoluminescence (PL) measurements are used to determine the rise time and decay rate of the PL intensity. Carriers are excited using an ultrafast laser pulse (~100 fs) at 4.5 µm, at a repetition rate of 250 kHz. PL from the sample is collected using reflective optics, and detected with a fast HgCdTe detector (3 ns temporal resolution). The PL signal is isolated from laser scattering using a longpass filter at 7.2 µm and recorded using a PCI card. Measurements made on a p-on-n homojunction LWIR detector structure based on an InAs/GaSb T2-SL on a GaSb substrate will be presented. The epi wafer was grown with a multi-wafer production molecular beam epitaxy reactor. Data are taken at 11 K and at 77 K, the anticipated operating temperature of the device. Peak PL intensity and PL lifetime are observed to increase with a decrease in temperature. The temporal evolution of PL at a carrier density of ~10^{16} cm^{-3} can be fit with a single exponential decay characterized by a time constant of 33 ns or 78 ns for 77 K or 11 K, respectively. This behavior suggests that nonradiative recombination dominates the recombination process, since the nonradiative lifetime increases with decreasing temperature while the radiative lifetime decreases with decreasing temperature. Under low injection conditions, the PL signal is proportional to the density of excess minority carriers. The measured PL lifetime increases with decreasing pump power, indicating that the injection density is higher than the background doping density. Therefore, the measured lifetime represents the lower bound for a LWIR detector under normal operating conditions. Preliminary measurements using lower pump powers indicate a PL lifetime greater than 60 ns at 77 K and 100 ns at 11 K.

1:50 PM Student

X2, MOCVD Growth of InAs/GaSb Type-II Superlattice Structures and Photodiodes for Mid-Infrared Detection: *Yong Huang*[1]; Jae-Hyun Ryou[1]; Russell Dupuis[1]; Adam Petschke[2]; Martin Mandl[2]; Shun-Lien Chuang[2]; [1]Georgia Institute of Technology; [2]University of Illinois at Urbana-Champaign

InAs/GaSb-based type-II superlattice (T2SL) structures have been exploited as photodetectors and light emitters operating in a wide wavelength range (from 3 µm to 32 µm) of the infrared (IR) spectral region. However, operating detectors based on this particular material system have been exclusively grown by molecular beam epitaxy (MBE). In this paper, we report on the metalorganic chemical vapor deposition (MOCVD) growth of InAs/GaSb type-II superlattices

and demonstrate the first MOCVD-grown InAs/GaSb T2SL photodiode. During the growth of the InAs/GaSb SL structures by MOCVD, gas switching and interfacial (IF) layer control are of critical importance. It was found that there exists an additional tensile strain in the InAs/GaSb SLs without any intentional interfacial layer (IF), presumably attributed to the formation of GaAs IF layer. InAsSb and InGaSb IF layers were thus introduced at the superlattice interfaces to compensate the tensile strain and hence to improve the overall material quality of the superlattice structures. The optimal morphology and low strain was achieved via a combined interfacial layer scheme with 1 monolayer (ML) InAsSb + 1 ML InGaSb layers. In this case the gas switching in one period is a smooth InAs -> InAsSb -> InGaSb -> GaSb -> InGaSb -> InAsSb -> InAs, and formation of any InSb- or GaAs-like interfaces is completely avoided. RMS roughness is only 0.172 nm for 20×20 µm^2 scan area and the separation between the SL 0th-order peak and the substrate is only ~448 arcsec, corresponding to an in-plane lattice mismatch of ~0.17%.Using this scheme, a p-i-n photodiode structure with a 360-period InAs/GaSb superlattice was grown on a GaSb substrate, which operates at 78 K with a cut-off wavelength of ~9 µm and a peak responsivity of 0.6 A/W at ~6 µm. The overall detectivity is $1.6×10^9$ Jones which is more than two orders of magnitude lower than those in state of the art InAs/GaSb-based T2SL devices for this wavelength grown by MBE. The performance degradation is attributed to the surface defects such as hillocks and high background doping levels in the InAs/GaSb i-SL. Nevertheless, these data show the first successful demonstration and feasibility of MOCVD-grown InAs/GaSb T2SL photovoltaic detectors. There is much room for improvement in the device performance through optimization of the material quality and MOCVD-oriented design of the device structure. Further work is currently being carried out on dry etching and surface passivation of the materials to enhance the sensitivity of the detectors.

2:10 PM Student

X3, Investigation of Passivation Techniques on InAs/GaSb Strained Layer Superlattice Long Wave Infrared Detectors: *Maya Narayanan Kutty*[1]; Elena Plis[1]; Stephen Myers[1]; Ha Sul Kim[1]; Nutan Gautam[1]; Ralph Dawson[1]; Sanjay Krishna[1]; [1]University of New Mexico

Considerable interest has been garnered by infrared (IR) detectors operating in the long wave IR (LWIR) spectral region (8–14µm) due to their wide ranging applications in the fields of medical diagnostics, meteorology, astronomy, search and rescue, missile detection, and satellite based surveillance. The available technologies in the current market at this wavelength range are Mercury-Cadmium-Telluride (MCT) and quantum-well-infrared (QWIP) detectors. MCT detectors face problems in the epitaxial growth of mercury-based compounds limiting manufacturing yield and QWIPs exhibit an inability to absorb normal incident light. The crucial advantage of InAs/(In,Ga)Sb strained layer superlattices technology is that its effective bandgap can be tuned within 3-32µm by modifying the individual material thicknesses. SLS technology also encompasses benefits such as normal incidence absorption, low tunneling currents, enhanced carrier lifetimes due to suppressed Auger-7 recombination processes, compositional uniformity over a large area and commercial availability of low defect density substrates. The reason InAs/ (In,Ga)Sb SLS detectors are yet to be commercialized is due to the detrimental effect of surface leakage currents on device performance. These surface leakage currents are a large component of the total dark current and they arise from abrupt termination of the crystal lattice at the surface leading to interfacial traps and dangling bonds and hence to the pinning of the Fermi level at the surface. Moreover, the native oxides formed due to the exposure to atmosphere are found to be conducting. These surface effects can be minimized by passivating the surface of the SLS devices and this presentation is a compilation of the results of passivating techniques we have undertaken on our LWIR SLS devices.The reported passivation study was performed on InAs/GaSb SLS LWIR detectors with p-i-n design grown by solid-source molecular-beam epitaxy (MBE) technique with the 100% cut-off wavelength ~ 11.7µm at 77K.The device structure was formed by 14ML InAs/7ML GaSb SLS non-intentionally doped (n.i.d) absorber grown on top of n-type contact layer (8ML InAs/8ML GaSb SLS with Te-doped InAs layers) and capped by GaSb p-type (Be) top-contact layer. Dark current measurements reveal the reduction of noise current by two orders of magnitude

after SU8 passivation (from 2.4A/cm2 for unpassivated device to 24mA/cm2 for passivated device, 30K, bias=-0.1V). At zero bias, R0A (SU-8 passivated)~ 13 x 10-2ohm-cm2 which is an order of magnitude larger when compared to R0A (unpassivated) ~ 22 x 10-3ohm-cm2. During the presentation the optical and electrical characteristics of SLS LWIR detectors (dark current density, resistance-area product at zero bias, responsivity and detectivity) studied for two different passivation treatments (SU-8 and SiNx) will be discussed in detail and compared with those reported in the literature for the p-i-n detectors operating in the same wavelength range.

2:30 PM Student

X4, Investigation of Antimonide Infrared Detectors Based on the nBn Design: *Stephen Myers*[1]; Arezou Khoshakhlagh[1]; Elena Plis[1]; Maya Kutty[1]; Ha Sul Kim[1]; Nutan Gautam[1]; Brianna Klein[1]; Ralph Dawson[1]; Sanjay Krishna[1]; [1]University of New Mexico

Infrared detectors are important tools with many wide ranging applications including defense, security, astronomy and medical diagnostics. The applications of infrared detectors are however limited by expensive and bulky cooling systems which are required for them to operate properly. The development of heterostructure designs capable of increasing operating temperature and reducing dark current density has thus become very important. Recently uni-polar designs utilizing barrier regions have gained much interest for achieving these characteristics. The nBn structure as developed by Maimon and Wicks utilizes an n-type contact region "n", a barrier region "B" with a large conduction band offset but no offset in the valence band, and a n-type absorber region. The large conduction band offset blocks electrons while allowing minority carriers to flow unimpeded. This design reduces dark current associated with generation-recombination (G-R) by alleviating the presence of a depletion region, as in the case of a p-i-n photodiode, making the detector diffusion limited at all temperatures. Another advantage that can be utilized with the nBn design is the suppression of surface leakage current which is a significant challenge of state of the art p-i-n designs, by utilization of shallow etching. In a typical p-i-n device, one pixel is distinguished from neighboring pixels by mesa isolation etching, however, with nBn shallow etching a pixel is distinguished from neighboring pixels by the minority carrier diffusion length. In order to fully capitalize on this design the different regions need to be optimized in terms of composition and doping level. The doping level is important because it dictates the offset of the bandstructure between the different regions. Previously, a study was conducted that investigated different doping levels of the absorber region of an InAs/GaSb superlattice nBn detector which revealed that careful tuning of the absorber doping level can improve device characteristics in terms of dark current density and detectivity. The barrier is a key component of the nBn design since it controls the flow of majority and minority carriers. It must be thick enough to prevent tunneling of majority carriers (electrons) and high enough to avoid thermal excitation in the conduction band. The doping level in the barrier region affects the valence band offset which impacts the behavior of the minority carriers (holes) consequently influencing the total dark and photo current of the detector. In this presentation a detailed study of the barrier region composition and doping level will be analyzed along with their impact on the device performance.

2:50 PM
X4, Late News

3:10 PM Break

3:30 PM Student
X6, Quinternary GaInAsSbP on GaAs Substrates Grown by Metal Organic Vapor Phase Epitaxy (MOVPE): *Toby Garrod*[1]; Peter Dudley[1]; Jeremy Kirch[1]; Sangho Kim[1]; Luke Mawst[1]; Thomas Kuech[1]; [1]University of Wisconsin-Madison

The capability to grow bulk lattice matched material, with band gap energies less than that of GaAs, is of interest for applications in concentrated photovoltaic devices. Material development is this area has focused on the incorporation of dilute amounts of nitrogen into conventional III/V crystals, although short minority carrier diffusion lengths, narrow depletion widths,

deep level defects and high carbon incorporation have limited the performance in MOVPE grown devices. The ability to grow narrow band gap material free of nitrogen would be advantageous for the electronic properties of these devices. Quinternary materials, although complex, offer a higher degree of freedom for materials development with knowledge of the incorporation properties of constituent elements. Recent reports of this material system were in the growth of mid-infrared light emitting diodes on GaSb substrates by liquid phase epitaxy (LPE) [1,2]. To our knowledge, there have been no reports of this material grown lattice matched GaAs by MOVPE. Growth studies have been performed on GaInAsSbP thin film alloys, grown on (100) GaAs substrates by MOVPE utilizing liquid group III and group V metal organic precursors. Room temperature photoluminescence studies of nominally lattice matched material to (100) GaAs substrates exhibits a band gap energy of 1.37 eV($Ga_{(0.76)}In_{(0.24)}As_{(0.25)}Sb_{(0.025)}P_{(0.725)}$, $\Delta a/a = 8.4 \times 10^{-4}$, V/III=67). High resolution x-ray diffraction (HRXRD), ω-2θ rocking curves around the (004) reflection for GaAs, were used to determine the lattice mismatch of the out-of-plane lattice parameter of the GaInAsSbP films. Due to the complex nature of the GaInAsSbP alloy, it is difficult to determine the composition by conventional measurements and assuming Vegard's Law. Therefore, calibrated secondary ion mass spectroscopy (SIMS) was used on selected samples to determine the actual solid phase compositions of the GaInAsSbP material. Future work with this material system will be to determine the lowest possible band gap energy for lattice matched material and to evaluate the effects of dilute amounts (<1%) of nitrogen into the GaInAsSbP material. This work is funded by Army Research Lab (ARL), contract number W911NF-09-2-0008. 1. A. Krier, V. M. Smirnov, P. J. Batty, M. Yin, K. T. Lai, S. Rybchenko, S. K. Haywood, V. I. Vasil'ev, G. S. Gagis and V. I. Kuchinskii, Appl. Phys. Lett. 91, 082102 (2007). 2. A. Krier, V. M. Smirnov, P. J. Batty, V. I. Vasil'ev, G. S. Gagis and V. I. Kuchinskii, Appl. Phys. Lett 90, 211115 (2007).

3:50 PM Student
X7, Growth of $GaAs_{1-x}Bi_x/Al_yGa_{1-y}As$ Multi-Quantum Well Structures on GaAs: *Takuma Fuyuki*[1]; Yoriko Tominaga[1]; Kazuya Yamada[1]; Kunishige Oe[1]; Masahiro Yoshimoto[1]; [1]Kyoto Institute of Technology

$GaAs_{1-x}Bi_x/Al_yGa_{1-y}As$ multi-quantum wells (MQWs) have been successfully grown by molecular beam epitaxy (MBE). Intensity oscillation and streaky patterns of *in situ* reflection high-energy electron diffraction (RHEED) suggested the layer-by-layer growth of $GaAs_{1-x}Bi_x/Al_yGa_{1-y}As$ MQWs. Clear satellite peaks attributed to periodical structures were observed in X-ray diffraction (XRD) measurements. Depth profile of secondary ion mass spectrometry (SIMS) confirmed periodical incorporation of Al and Bi. The cross-sectional transmission microscopy (TEM) images showed that $GaAs_{1-x}Bi_x/Al_yGa_{1-y}As$ MQWs with a smooth interface can be fabricated without distinct segregation. III-V semiconductor alloys including semimetallic components, such as $GaAs_{1-x}Bi_x$ with semimetallic GaBi, have been proposed as materials having temperature-insensitive bandgaps. The material with a temperature-insensitive bandgap is expected to be applicable to a laser diode (LD) of which the wavelength is kept constant against ambient temperature variation. The MQW is a key structure for fabrication of LDs. As Bi was utilized as a surfactant in the growth of III-V semiconductors, it was segregated easily during the growth. We demonstrated that low-temperature growth (<400ºC) efficiently suppressed segregation of Bi atoms, and $GaAs_{1-x}Bi_x/GaAs$ MQWs were successfully realized without distinct segregation in previous study. It is notable that $GaAs_{1-x}Bi_x$ showed brightly luminescent nature in spite of the low-temperature growth. This implies that Bi atoms play some role in improving crystalline quality during the growth. In this study, we have extended the growth technique to $GaAs_{1-x}Bi_x/Al_yGa_{1-y}As$ MQWs toward efficient carrier confinement. $GaAs_{1-x}Bi_x/Al_yGa_{1-y}As$ MQWs (0.03< x <0.05, 0< y <0.3) were grown on GaAs(001) substrates by MBE at a substrate temperature of 350ºC. The thicknesses of $Al_yGa_{1-y}As$ and $GaAs_{1-x}Bi_x$ layers were designed to be 14 and 7 nm, respectively, with a periodical number of 10. In RHEED observation, a (2x1) superstructure was observed during the growth of $GaAs_{1-x}Bi_x$ layers in contrast with a (1x1) patterns during growth of $Al_yGa_{1-y}As$ layers. Persistent RHEED intensity oscillation was observed as well as the streaky RHEED patterns during both layers, suggesting layer-by-layer growth of $GaAs_{1-x}Bi_x/Al_yGa_{1-y}As$ MQWs. Clear satellite peaks attributed to

periodical structures were observed in XRD measurements. Thickness of each period derived from the position of satellite peaks agreed with designed values for all MQWs. This indicates that fabrication of $GaAs_{1-x}Bi_x/Al_yGa_{1-y}As$ MQW structures can be controlled precisely without a distinct diffusion of Bi atoms. Depth profile of SIMS confirmed periodical incorporation of Al and Bi. TEM images with low magnification demonstrated fabrication of the quantum-well structure with a smooth interface. Clear lattice images are observed for both the $Al_yGa_{1-y}As$ and $GaAs_{1-x}Bi_x$ layers in the high-magnification TEM images. It is concluded that the $GaAs_{1-x}Bi_x/Al_yGa_{1-y}As$ MQWs with a smooth interface can be fabricated without distinct segregation.

4:10 PM Student

X8, Perforated (In)GaSb Quantum Wells on GaSb Substrates through the Use of As₂ Based In-Situ Etches: *P. Ahirwar*[1]; T. J. Rotter[1]; S. Clark[1]; C. P. Hains[1]; A. R. Albrecht[1]; L.R. Dawson[1]; G. Balakrishnan[1]; [1]Center for High Technology Materials, University of New Mexico

The InGaSb quantum wells (QW) represent a very promising technology for room-temperature mid-Infrared semiconductor lasers. These wells are grown under very high strain conditions and their emission can reach very long wavelengths if the strain in the wells is managed. The high strain has the added advantage of suppressing Auger non-radiative recombination in the wells. Traditional approaches for growing highly strained active regions include strain compensation and low-temperature growth. However, even these techniques can only accommodate a slightly elevated level of strain. Another option for the growth of highly strained active regions is the use of the Stranski-Krastanov (SK) growth mode to produce quantum dots. However, the SK growth mode is not viable in the III-Sb material system since highly strained (>5% mismatch) antimonide layers tend to form completely relaxed islands through interfacial misfit dislocation arrays. In this paper we present the growth of perforated InGaSb QW on a GaSb substrate. The growth of the material is done in a VG V80 molecular beam epitaxy (MBE) reactor. The InGaSb quantum wells are grown with a variety of thicknesses and are subsequently etched by an As₂ flux. The As₂ etches into the antimonide material resulting in nano-scale holes in a random pattern. The presence of these holes permits the InGaSb layer to relax in the in-plane direction thus relieving a significant amount of the strain. The study includes the growth of single InGaSb QWs with the In percentage varying from 0 to 60%. The samples are exposed to a variety of As₂ fluxes at different growth temperatures to study etch rate and etch profile. The samples are analyzed using atomic force microscopy, scanning electron microscopy, transmission electron microscopy and high-resolution x-ray diffraction. Samples with intact wells and with etched wells are compared and the difference in strain is measured. The effect of the etching process on the quantum wells is investigated using photoluminescence. In order to ensure, that the etch does not progress beyond the quantum well, etch stop layers are investigated. We have identified thin layers of InAs as a potential etch stop layer. Most of the present results are based on low-Indium percentage QWs and we will study how the etch process will change in the presence of high-Indium percentage QWs. The capping process of a perforated well is non-trivial. Currently the cap layers are grown such that they coalesce over the voids. Alternately the growth can also be performed such that the voids are completely filled. We shall also investigate the presence of threading dislocation in the growth due to the capping process. Finally, we shall study how the excess arsenic (etchant) incorporates into the matrix.

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X9, Antimonide VECSELs on AlGaAs DBRs: P. Ahirwar[1]; *T. J. Rotter*[1]; A. R. Albrecht[1]; S. Clark[1]; C.P. Hains[1]; L. R. Dawson[1]; G. Balakrishnan[1]; J. V. Moloney[2]; [1]Center for High Technology Materials (CHTM), University of New Mexico, Albuquerque, NM 87106; [2]College of Optical Sciences, University of Arizona, Tucson, AZ 85721

We present an optically pumped vertical-external-cavity surface-emitting laser (VECSEL) with high output power at 2 μm achieved through the integration of III-Sb active regions with AlGaAs Distributed Bragg Reflectors (DBRs)[1]. The laser's active region includes GaInSb/AlGaSb type I quantum wells. The optical cavity is provided by a high reflectivity AlGaAs/GaAs DBR and an external mirror which also serves as the output coupler. The novelty in this approach is

the combination of a GaSb based active region with a GaAs based DBR, both of which are monolithically grown on a GaAs substrate[2]. The strain due to the lattice mismatch between the GaSb-based active region (lattice constant close to 6.1 Å) and the GaAs-based DBR (lattice constant close to 5.65 Å) is relieved by the formation of an interfacial misfit (IMF) array at the GaSb/GaAs interface[3,4]. GaSb based VECSELs were previously grown on GaSb based DBRs. While high power devices have been achieved with this technology, the device performance is limited by a smaller index contrast of GaSb based DBRs compared to GaAs based DBRs and higher absorption of the laser's emission in GaSb compared to GaAs. The work described in this talk is based on crystal growth by molecular beam epitaxy (MBE), along with the basic crystal characterization techniques such as X-ray diffraction (XRD), photoluminescence (PL), surface nomarski microscopy and atomic force microscopy (AFM). We shall also provide detailed lasing data for lasers at 2 μm both pulsed and CW. We shall discuss the technical challenges related to the MBE growth of such structures, which are numerous. First, the IMF based growth of III-Sb on GaAs leads to differences in strain and relaxation of the epilayer as compared to growth on GaSb substrates. This influences the optical emission from the III-Sb active region, since it depends on the compressive strain in the quantum wells. It requires an independent development of the active region, grown on GaAs. Second, the transfer of the IMF growth technology from growth on GaAs substrates to growth on the MOCVD grown AlGaAs/GaAs DBR is nontrivial. The challenges include the IMF formation on the DBR surface, which is slightly rougher than a GaAs substrate's surface, and the growth temperature control, since the DBR's heat conductivity differs from that of a GaAs substrate. We shall also discuss the development of longer wavelength VECSELs in the MWIR (2.5 to 3.5 μm). This discussion will include active region development and DBR performance at these wavelengths.

4:50 PM Student

X10, Effect of Aluminum Composition on Current-Voltage Characteristics of AlGaSb/InAs Tunnel Junction: *Yeqing Lu*[1]; Alan Seabaugh[1]; Huili Xing[1]; Tom Kosel[1]; Siyuranga Koswatta[2]; Hanjun Zhu[3]; Kevin Clark[3]; Jenn-Ming Kuo[3]; Pinsukanjana Paul[3]; Patrick Fay[1]; [1]University of Notre Dame; [2]IBM T. J. Watson; [3]IntelliEPI

Tunneling field effect transistors (TFETs) with staggered band alignment have recently attracted considerable interest because of their potential use in low power, high performance logic applications. The low tunneling barrier height and small effective mass in AlGaSb/InAs heterostructures may enable high tunneling current density, and the large band gap of AlGaSb suppresses off-state current. However, little experimental study has been done of the band alignment in this material system as a function of ternary composition. In this work, a set of $Al_xGa_{1-x}Sb$/InAs samples was grown by molecular beam epitaxy (MBE), and heterostructure tunnel diodes were fabricated. Secondary ion mass spectroscopy (SIMS) was used to measure the dopant and aluminum profiles, and current-voltage (I-V) and low temperature I-V were measured to characterize the tunneling junction. The MBE growth used Be and Si as the dopant species for p-AlGaSb and n-InAs respectively. At the interface between AlGaSb and InAs, the dopant flux was turned off, resulting in a 2 nm thick unintentionally-doped AlGaSb layer at the P+/N+ junction. The samples were capped with highly doped GaSb to facilitate ohmic contact. A Be dopant slope of 23 nm/decade at the tunnel junction was observed in the SIMS profile. Devices were fabricated using a self-aligned process to minimize access resistance. A Ti/Au/Ti emitter was first formed by lift-off on the P+ GaSb layer, followed by selective wet etching of the AlGaSb in 1:5 NH_4OH:H_2O and the InAs in 1:2 citric acid:H_2O_2 to form the mesa. This metallization has been previously found to minimize mesa etch undercut [1]. The self-aligned bottom contact is then formed by electron beam evaporation of a Ti/Au contact. Current-voltage characteristics for diodes fabricated with different Al mole fractions (x=0, 0.12, 0.2, and 0.27 as determined by SIMS) were compared. The corresponding peak current densities were measured (0.048, 0.13, 0.22, 0.5 mA/μm²) and found to decrease as expected with increasing Al content. From [2], the band alignment is expected to transition from broken to staggered at x=0.4. However, due to lower-than-expected Al incorporation, the highest Al composition achieved experimentally was 0.28, and this diode clearly demonstrates negative differential resistance

(NDR) indicating that the bands have not yet crossed. In addition, due to the low effective mass and the relatively high doping concentration, significant degeneracy in the InAs may also be contributing. From temperature dependent measurement, peak current almost does not change with temperature, but valley current shows a thermionic character as expected. This work is supported by the Nanoelectronics Research Initiative (NRI) through the Midwest Institute for Nanoelectronics Discovery (MIND).

Session Y: III-N Nanostructures

Thursday PM
June 24, 2010

Room: 138
Location: University of Notre Dame

Session Chairs: Andrew Armstrong, Sandia National Laboratories; Alec Talin, NIST

1:30 PM Student

Y1, Dislocation Filtering in GaN Nanorods: *Robert Colby*[1]; Zhiwen Liang[1]; Isaac Wildeson[2]; Timothy Sands[3]; R. Garcia[1]; Eric Stach[1]; [1]Purdue University, School of Materials Engineering; [2]Purdue University, School of Electrical and Computer Engineering; [3]Birck Nanotechnology Center

Dislocation filtering in GaN by selective area growth through a nanoporous template is examined both by transmission electron microscopy and numerical modeling. These nanorods grow epitaxially from the (0001)-oriented GaN underlayer through the ~100 nm thick template and naturally terminate with hexagonal pyramid-shaped caps. It is demonstrated that, for a certain window of geometric parameters, a threading dislocation growing within a GaN nanorod is likely to be excluded by the strong image forces of the nearby free surfaces. Approximately 3000 nanorods were examined in cross-section, including growth through 50 nm and 80 nm diameter pores. The very few threading dislocations not filtered by the template turn towards a free surface within the nanorod, exiting less than 50 nm past the base of the template. The potential active region for light emitting diode devices based on these nanorods would have been entirely free of threading dislocations for all samples examined. A greater than two orders of magnitude reduction in threading dislocation density can be surmised from a data set of this size. A finite element-based implementation of the eigenstrain model was employed to corroborate the experimentally observed data and examine a larger range of potential nanorod geometries, providing a simple map of the different regimes of dislocation filtering for this class of GaN nanorods. These results indicate that nanostructured semiconductor materials are effective at eliminating deleterious extended defects, as necessary to enhance the optoelectronic performance and device lifetimes compared to conventional planar heterostructures.

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Y2, Threading Defect Elimination in GaN Nanostructures: *Ashwin Rishinaramangalam*[1]; Stephen Hersee[1]; Michael Fairchild[1]; Lei Zhang[2]; Petros Varangis[2]; [1]The Center for High Technology Materials, The University of New Mexico; [2]Nanocrystal Corporation

This paper describes the elimination of threading dislocations (TDs) in GaN nanowire and nanowall structures grown by Metal Organic Chemical Vapor deposition (MOCVD). The templated nanostructure growth process uses high-purity metal organic and ammonia precursors as in regular MOCVD growth, and avoids the use of metal catalysts. The nanostructures were grown selectively onto underlying planar (0001) GaN films using nano-patterned templates. The threading defect density in the underlying planar GaN film was in the range 10^8 to 10^9 cm^{-2}. TDs were imaged using bright-field cross-sectional transmission electron microscopy (XTEM) analysis of thinned nanowire and nanowall samples. The density of threading defects in [0001] GaN nanowires approaches zero even though these nanostructures are epitaxially connected to an underlying planar GaN film that has a defect density in the range 10^8 to 10^9 cm^{-2}. XTEM reveals that the nominal [0001] line direction of a TD changes when that TD enters a GaN nanostructure. The line direction of the TDs bends towards the (0001) plane, and the dislocation rapidly terminates at a {1-100} sidewall facet of the nanostructure. We propose that the driving force for this elimination process is the reduction of the dislocation line energy. This line energy is reduced for a TD that bends and terminates at a sidewall compared to a TD that continues to propagate along the nanowire. A simple model is also proposed, where in the TDs are shown to bend and terminate at a sidewall simply by climb. A conversion to another defect-type does not appear to be required and furthermore, conversion to a different defect is expected to be energetically unfavorable. This TD elimination mechanism is expected to be active in any [0001] GaN nanostructure, where a surface is in close proximity to the threading defect. Nanostructures clearly offer a unique opportunity to fabricated defect-free GaN-based devices.Acknowledgment: This work was supported in part by the Engineering Research Centers Program of the National Science Foundation under NSF Cooperative Agreement No. EEC-0812056. Any Opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of the National Science Foundation.

2:10 PM Student

Y3, Yellow-Orange Luminescence from III-Nitride Nanopyramid Heterostructures: *Isaac Wildeson*[1]; David Ewoldt[1]; Robert Colby[1]; Zhiwen Liang[1]; Dmitri Zakharov[1]; R. Edwin Garcia[1]; Eric Stach[1]; Timothy Sands[1]; [1]Purdue University

One of the current major thrusts in the light emitting diode (LED) research community is developing a solution for the "green gap" – that is, the current lack of an efficient yellow-green LED technology. Of the available materials systems, the III-nitrides currently appear as the most promising for resolving the green gap and extending the range of efficient luminescence across the visible spectrum in a single materials system. The III-nitrides, however, possess numerous challenges including high threading dislocation densities, a large lattice mismatch and miscibility gap between InN and GaN, and strong polarization-induced electric fields within quantum wells. The focus of the current work is to utilize nanoheteroepitaxy for quantum well growth in an attempt to mitigate both the high threading dislocation density and the large lattice mismatch between GaN and InN. Theoretical investigations have illustrated that the effective critical thickness of a heterostructure can be significantly increased if growth is conducted on nanostructures that allow lateral strain relaxation [1]. Specifically, our work focuses on selective-area organometallic vapor phase epitaxy of III-nitride nanopyramid heterostructures through dielectric growth masks that accurately control the size and position of the nanopyramids, as well as serve as effective dislocation filters for threading dislocations within the underlying GaN films [2]. Furthermore, by varying the growth parameters, the geometry of the nanopyramids can be altered at specific stages of the heterostructure growth to produce active regions that are either predominantly quantum wells or predominantly quantum dots. We will discuss in detail the luminescent properties of nanopyramid heterostructures by analyzing both photoluminescence (PL) and electroluminescence (EL) results. Temperature-dependent PL measurements often used for estimations of internal quantum efficiency yield a ratio of the integrated PL intensity at 300K over the integrated PL intensity at 4K of 10.3%. PL also reveals a change in peak emission energy with temperature that follows a "double s-shape" (red-shift, blue-shift, red-shift, blue-shift), instead of the commonly observed single "s-shape" (red-shift, blue-shift, red-shift). The origin of the "double s-shaped" PL trend may result from two distinct groups of indium-rich clusters that produce band-tail states, or may result from contributions of yellow defect luminescence at high temperatures. EL reveals a 45 nm red-shift between nanopyramid LEDs and thin-film LEDs that were grown together, suggesting higher InN incorporation in the strain-relaxed nanopyamids during growth. This material is based in part on work supported by the Department of Energy under Award No. DE-FC26-06NT42862. [1]. E. Ertekin, et.el., J. Appl. Phys. 97, 114325 (2005). [2]. P. Deb, et.el., Nano Lett. 5, 1847 (2005).

THURSDAY PM

2:30 PM Student

Y4, Molecular Beam Epitaxial Growth and Characterization of InGaN/ GaN Dot-in-a-Wire Nanoscale Heterostructures on Si: *Jiale Wang*[1]; Yi-Lu Chang[1]; Feng Li[1]; Zetian Mi[1]; [1]McGill University

There has been an escalating interest in developing high efficiency green and red emitting InGaN/GaN LEDs for all LED and smart lighting applications. Such devices, however, generally exhibit very low internal quantum efficiencies, due to the presence of large defect densities and the strain induced polarization field. Greatly reduced defect densities and strain distribution, on the other hand, can be achieved in nanowire heterostructures, due to the effective lateral stress relaxation. Additionally, the use of quantum dots further provide 3-dimensional carrier confinement and drastically reduced nonradiative carrier recombination associated with the presence of surface states. In this context, we have studied the molecular beam epitaxial (MBE) growth and characterization of nearly defect-free InGaN/GaN dot-in-a-wire as well as dot-on-a-wire nanoscale heterostructures on Si(111) substrates, which exhibit strong emission in the green, yellow, and red wavelength range, with an internal quantum efficiency of ~ 45%. The nanowire heterostructures were grown on Si(111) substrates using a Veeco Gen II MBE system equipped with a radio frequency plasma source. The wires exhibit diameters of ~ 30 – 50 nm and are of a wurtzite structure and aligned along the c-axis. The high resolution TEM analysis confirms that the InGaN quantum dots and surrounding GaN barrier layers are nearly free of dislocations. It is also observed from the detailed TEM analysis that each InGaN dot is not compositionally uniform, with the presence of In-rich nanoclusters, due to phase segregation. However, such In-rich nanoclusters are not observed for InGaN quantum dots grown GaN nanowires without any capping layer. Optical properties of InGaN/GaN dot-in-a-wire nanoscale heterostructures were investigated using temperature-variable photoluminescence spectroscopy. By varying the In compositions in the dots, we have achieved strong green, yellow, and amber emission, which exhibit a relatively high room temperature internal quantum efficiency of ~ 45% of that measured at ~ 10 K. In addition, strong red emission ($\square$ ~ 0.66 µm) has been measured from InGaN/GaN dot-on-a-wire nanoscale heterostructures. The photoluminescence intensity of the red-emitting InGaN quantum dots is nearly a factor of 2 of that of GaN, in spite of the much thicker GaN segments, compared to the dots, which further confirms the excellent optical quality of InGaN quantum dots. Optical properties of single InGaN/GaN dot-in-a-wire nanoscale heterostructures, as well as the achievement of green and red-emitting InGaN/GaN dot-in-a-wire LEDs on Si are being investigated and will be presented.

2:50 PM Student

Y5, Electrochemical Etching of GaN and Its Applications: *Yu Zhang*[1]; Qian Sun[1]; Chris Yerino[1]; Benjamin Leung[1]; Qinghai Song[1]; Coung Dang[1]; Sang-wan Ryu[2]; Hui Cao[1]; Arto Nurmikko[3]; Jung Han[1]; [1]Yale University; [2]Chonnam National University; [3]Brown University

The importance of GaN devices in display, data storage, and lighting applications is clearly established by now. In a more forward-looking manner, one may rightly ask about new opportunities the wide bandgap III-nitride family could offer, and new dimensions one could introduce to the existing technologies. In this talk we describe an electrochemical procedure to selectively etch conducting n-type GaN layers. We also present a few proof-of-concept demonstrations of device structures facilitated by this simple method of etching. Wet etching of Ga-polar GaN at room temperature can only be done through photoelectrochemical (PEC) etching method where photoexcited holes as minority carriers mediate an oxidation-etching mechanism. This procedure has been incorporated into a selective etching technique with a combination of epitaxial heterostructures (InGaN/GaN) and bandgap selective photoexcitation. Recently, a few groups have pursued the wet-etching of "GaN-compatible" layers, layers that have sufficiently different chemical compositions and are more amenable to wet-etching. Two of such GaN-compatible layers are AlInN and CrN, and there have been already interesting demonstrations. Our work in based on a recent observation that a heavily doped (N_D>2x10^{18}cm^{-3}) GaN can be selectively etched in an oxalic-acid electrochemical etching. Distinct advantages of using n-GaN as the "sacrificial layer" for etching include (1) complete lattice matching to conventional GaN structures with negligible degradation in microstructure or

morphology, (2) complete freedom in thickness design toward 1D, 2D, and 3D photonic-electronic-mechanical structures, and (3) the possibility of tuning the etching pathways at microscale through conductivity, bias, and solution, thus offering a new tool set to etch, to undercut, and to "texture" GaN. Figure 1(a) and (b) show GaN microdisk array and preliminary result of mode pattern of a microdisk (10 µm diameter) under optical pumping, Figure 1(c) shows the formation of GaN microdisk where the lower cladding is nanoporous GaN in stead of air, thus greatly improving the structural robustness. The effect of optical confinement can be seen from the contrast of annular rings under Nomarski (Figure 1(d)), figure 1(e) shows another example of lateral undercut etch in forming distributed Bragg reflector (DBR) structures. It is worth noting that under reduced bias or doping level, nanoporous GaN is produced as a new class of GaN material with tunable index of refraction for photonic structure. Figure 1(f) illustrates the use of nanoporous GaN for form a three-period DBR. Figure 2 show (a) a GaN cantilever prepared by the EC etching and (b) Spectral response of a GaN cantilever compared with a reference spectrum. The reference was obtained at un-etched wafer surface. Figure 3 shows the nanocrystal GaN obtained by sonicating nanoporous GaN in DI water.

3:10 PM Break

Session Z: Point and Extended Defects and Doping in Wide Bandgap Materials

Thursday PM   Room: 138
June 24, 2010   Location: University of Notre Dame

Session Chairs: Alec Talin, NIST; Andrew Armstrong, Sandia National Laboratories

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Z1, Luminescence Recombination Dynamics of Ytterbium Implanted GaN Epilayers: Wojciech Jadwsienczak[1]; *Jingzhou Wang*[1]; Andre Anders[2]; [1]Ohio University; [2]Lawrence Berkeley National Laboratory

In the past Yb-doped III-V semiconductors were extensively investigated due to the relative simplicity of the Yb^{3+} electronic structure (4f^{13}). Those studies proved to be useful in better understanding of other RE^{3+} ions doped III-V semiconductors. During the last few years rare earth (RE) ions doped III-nitride (III-N) semiconductors received significant interests because their unique luminescence and magnetic properties [1,2]. Among investigated RE-doped III-Ns ytterbium has been the least studied. Recent theoretical calculations predict that the Yb^{3+} ion can occupy different optically active centers in GaN and AlN hosts [3,4].In this project we investigated Yb^{3+} ions implanted to GaN grown by hydride vapor phase epitaxy (HVPE) on (0001) Sapphire and GaN grown by metal-organic chemical vapor deposition (MOCVD) on (0001) Sapphire, respectively. The photoluminescence and photoluminescence kinetics of these samples have been studied with continuous and pulse photo-excitations in 360 nm – 1100 nm spectra range at different temperatures. The characteristic Yb^{3+} ion emission spectra were observed between 970 nm -1050 nm. There are more emission lines than predicted by theory for Yb^{3+} ions occupying a C_{3v} symmetry site in the GaN host. The number of luminescence transition lines observed at low temperature between the spin-orbit levels $^2F_{5/2}$-$^2F_{7/2}$ indicates that Yb^{3+} ions are involved in different optically active centers. Luminescence kinetics results confirmed that Yb^{3+} ions occupy at least two major distinct lattice site locations. Based on obtained experimental data we will discus the excitation mechanism for Yb^{3+} ions in GaN which can be generalized for all RE^{3+} ions in III-Nitride semiconductors. Furthermore, better understanding of the structural and opto-electrical properties of Yb^{3+} ion in GaN may find useful in energy harvesting applications where Yb^{3+} ion works as sensitizer. [1] J. H. Park, and A. J. Steckl, J Appl. Phys., Vol. 98, 056108 (2005). [2] H. J. Lozykowski, and W. M. Jadwisienczak, phys. stat. sol (b), Vol.244, 2109 (2007). [3] M. Dammak, S. Kammoun, R. Maalej, T. Koubaa, and M. Kamoun, J. Alloys Compd.,, Vol.18, 432 (2007).[4] T. Koubaa, M. Dammak, M. Kammoun, W. M. Jadwisienczak, H. J. Lozykowski, and A. Anders, J. Appl. Phys. Vol.106, 013106 (2009).

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Z2, Energy Levels of Nd³⁺ Ions in *In Situ* Doped AlN: *Grace Metcalfe*[1]; Eric Readinger[1]; Ryan Enck[1]; Paul Shen[1]; Michael Wraback[1]; [1]US Army Research Laboratory

Rare-earth (RE) doped semiconductors have found many applications in solid-state lasers, light-emitting displays and devices, and optical fiber telecommunications. Wurtzite nitrides are particularly attractive host materials due to their strong ionic bonds that can enhance the intra-4fn transition probability in the RE^{3+} ion, and high thermal conductivity necessary for maximizing performance of high power/high temperature devices. In addition, it has been shown that thermal quenching decreases with increasing band gap, making the widest band gap nitride AlN an appealing host material. AlN doped with RE ions, particularly Er and Eu, has been extensively studied. However, little is known about AlN doped with Nd, which has found immense success as the dopant in solid state lasers (i.e. Nd:YAG and Nd:YVO$_4$). In this paper, we report on *in situ* doping with Nd of AlN grown by plasma-assisted molecular beam epitaxy (PA-MBE). The Stark energy levels of the Nd^{3+} ion in AlN are resolved by photoluminescence (PL) and photoluminescence excitation (PLE) spectroscopy. The AlN layer was grown on *c*-plane sapphire by PA-MBE and consists of an AlN buffer layer followed by a ~0.6 µm-thick Nd-doped AlN layer. The sample was cooled to ~ 13K and pumped with a continuous wave Ti: Sapphire laser tunable between 750 to 1000 nm and with an excitation power of ~350 mW. The resulting luminescence was collected into a spectrometer and onto a Ge detector. Strong emission is observed at low temperature in the PL spectrum due to transitions from the $^4F_{3/2}$ doublet to the $^4I_{9/2}$, $^4I_{11/2}$, and $^4I_{13/2}$ manifolds. Due to the crystal field experienced by substitutional Nd-ions at Al sites, there are a total of $J+1/2$ Stark sublevels in each manifold, where J is the total angular momentum. The PL peaks appear in pairs separated by 5.0 meV, indicating the splitting energy of the $^4F_{3/2}$ doublet. The most intense emission peaks are observed from transitions to the $^4I_{11/2}$ manifold, with the strongest emission line at 1.12 eV (1108 nm). The PLE spectrum detected at the strongest emission energy 1.12 eV (1108 nm) at low temperature shows transitions from the $^4I_{9/2}$ ground state to the upper states $^4F_{5/2}$, $^2H_{9/2}$, $^4F_{7/2}$, and $^4S_{3/2}$. The strongest emission occurs at an excitation energy of 1.48 eV (835 nm). The energy levels of Nd in AlN are slightly shifted with respect to those which we previously measured in PA-MBE grown GaN, as evidenced by the splitting energy of the $^4F_{3/2}$ doublet (4.2 meV in GaN versus 5.0 meV in AlN). The shifted energy levels are due to the changes in the environment experienced by the Nd ions in AlN as compared to GaN, most likely caused by differences in the crystal-field or strain with substitutional doping at the Ga or Al site.

4:10 PM

Z3, Correlation of InGaN Growth Parameters, Defects and MQW Radiative Efficiency for Blue to Green Emission: *Andrew Armstrong*[1]; Mary Crawford[1]; Daniel Koleske[1]; Stephen Lee[1]; [1]Sandia National Laboratories

Deep-green emitting light emitting diodes are necessary for multi-chip color mixing for higher efficiency solid-state lighting. However, the internal quantum efficiency (IQE) of $In_xGa_{1-x}N$/GaN multi-quantum wells (MQWs) decreases as x increases to extend the emission wavelength from blue to green. The cause for this "green gap" is not fully understood. The quantum-confined Stark effect (QCSE) decreases IQE of *c*-plane $In_xGa_{1-x}N$/GaN MQWs with increasing x. However, reduced efficiency at longer wavelengths is observed for non-polar $In_xGa_{1-x}N$/GaN LEDs, where the QCSE is not operative, suggesting that non-radiative recombination centers (NRCs) play an important role, too.[1] Increasing x enhances strain in the InGaN well and requires reduced InGaN growth temperature (T_g), which can increase defect populations. Hence, understanding the influence of InGaN-related defects and controlling their incorporation is important for optimizing InGaN/GaN MQWs for green emission. To quantitatively correlate InGaN growth conditions with defect incorporation and study the resultant impact on the IQE of $In_xGa_{1-x}N$/GaN MQWs, we combined deep level optical spectroscopy (DLOS) with lighted capacitance-voltage (LCV) and photoluminescence. The properties and densities of deep level defects in coherently-strained $In_xGa_{1-x}N$/GaN (x=0.17,0.21) epi-layers were compared to the change in MQW IQE at 450 nm (x=0.17) versus 540 nm (x=0.21). *c*-plane InGaN epi-layers used for DLOS and InGaN wells in the MQW samples were

grown under nominally the same conditions. To asses the influence of InGaN T_g on defect incorporation and IQE independent of polarization or strain effects, $In_{0.17}Ga_{0.83}N$/GaN MQWs were grown with 690C<T_g<760°C while holding constant other MQW growth and structural parameters. A 3.6x decrease in IQE was observed with reduced T_g and attributed to excess defect incorporation, since the QCSE was constant in these samples. DLOS and LCV study of corresponding epi-layers grown at 690°C and 750°C confirmed an $In_{0.17}Ga_{0.83}N$ deep level 1.7 eV above the valence band, whose density increased 3x for reduced T_g. We hypothesized that the 1.7 eV deep level is a NRC degrading IQE. To study the potential role of the 1.7 eV in the "green gap," $In_{0.21}Ga_{0.79}N$/GaN MQW and DLOS samples were grown at 730°C. A sharp drop in IQE coincident with a 4x increase in [1.7 eV] for $In_{0.21}Ga_{0.79}N$ relative to $In_{0.17}Ga_{0.83}N$ films was observed. Greater enhancement of [1.7 eV] for only a 20°C reduction in T_g when indium was also increased suggests that reducing T_g and increasing indium content act in concert to enhance defect incorporation and degrade IQE. Possible origins and potential mitigation of the 1.7 eV level will be discussed. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract No. DE-AC04-94AL85000. 1. H. Yamada et al. Appl. Phys. Exp. 1 041101 (2008).

4:30 PM Student

Z4, Proton-Irradiated AlGaN/GaN HEMT at 5 MeV Protons: *Hong-Yeol Kim*[1]; Jihyun Kim[1]; Jaime Freitas, Jr.[2]; Michael Mastro[2]; [1]Korea University; [2]US Naval Research Laboratory

The efficiency and compact footprint of AlGaN/GaN high electron mobility transistor (HEMT) based circuits are attractive for communications applications in satellites. In low earth orbit, high energy protons bombard onto the device, which can cause degradation of the electrical properties. The optical and electrical properties of AlGaN/GaN epilayers grown on sapphire irradiated with high energy proton were investigated by low-temperature photoluminescence (PL) spectroscopy (with the 325 nm line of a He-Cd laser) and current-voltage measurements. The proton energy and fluence were 5 MeV and 2x10¹⁵ protons/cm², respectively. PL results prior to and after HEMT irradiation showed that the near bandedge peak at 355 nm decreased by 94 % as compared with that of the un-irradiated sample. In this PL data, two new lines at 350.27 and 359.53 nm were observed after irradiation, indicating that high-energy protons introduce defects within the structure, which reduce the intensity of the near bandedge emission band and lead to a disorder-generated LO phonon band. Electrical properties of the irradiated AlGaN/GaN were characterized to examine the role of the defects introduced by proton-irradiation. After proton irradiation, saturation current (I_{DS}-V_{DS}) decreased by 46 % at a 6 V source-drain voltage and 0 V gate voltage. The electrical parameters were relatively less sensitive than the optical parameters to the effects of proton irradiation. This suggests that the two-dimensional electron gas at AlGaN/GaN interface was very resistant to the proton irradiation. A simulation suggested that a thin electron channel is easily disrupted under low energy irradation but is transparent to higher energy protons. In contrast, the simulation suggests a thicker channel region presents a larger volume to absorb high energy protons and create deleterious defects.

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Z5, Effect of Traps Spatial Localization on GaN HEMT Static Characteristics: *Alessandro Chini*[1]; Valerio Di Lecce[1]; Michele Esposto[1]; Gaudenzio Meneghesso[2]; Enrico Zanoni[2]; [1]Università di Modena e Reggio Emilia; [2]Università di Padova

GaN HEMTs are continuously showing their impressive potential for RF and power switching application. Nevertheless their reliability still needs to be investigated in order to use them in commercial and military applications. Several authors have reported performance degradation both in the dynamic and static characteristics [1,2,3,4] of GaN HEMTs due to the formation of trap states [1,4] within the AlGaN barrier layer when high electric fields are applied to the gate-drain device junction. In this work we discuss how trap state formation during reverse gate-source and gate-drain step-stress tests can affect device static characteristics, and show through numerical simulations how the observed degradation can be explained by means of localized defects at the gate-source

or gate-drain edge in the AlGaN barrier. The devices tested were GaN HEMT grown on SiC substrates with a total gate periphery of 4x25µm and a 0.3µm gate length. Part of the devices tested were step-stressed by applying a negative gate-drain voltage of -2.5V/step for a total time of 5 minutes with the source terminal left open, while other devices were step-stressed by applying a negative gate-source voltage of -2.5V/step for a total time of 5 minutes with the drain terminal left open. In both cases device static I-V characteristics remained unchanged up to reverse voltage of approximately 25V after which a significant increase in reverse current as well as a decrease in DC current levels were observed. Gate-drain stressed devices showed an increase in output conductance as well as a softening of the knee-voltage while gate-source stressed ones showed a reduction of DC current levels in the I-V characteristics whose still showed a sharp knee and a low output conductance. Numerical Simulations carried out by means of the commercial DESSIS-ISE (Synopsis Inc.) simulator showed that acceptor traps placed at 0.5eV from the conduction band at the gate-drain or the gate-source edge within the AlGaN barrier can qualitatively explain the observed different devices degradation when applying gate-drain or gate-source high electric fields. [1] Joh Jungwoo et al., "Impact of Electrical Degradation on Trapping characteristics of GaN High Electron Mobility Transistors", IEEE IEDM 2008, Dec. 2008. [2] A. Chini et al., "Correlation between DC and rf degradation due to deep levels in AlGaN/GaN HEMTs", IEEE IEDM 2009, Dec. 2009. [3] E. Zanoni et al., "Localized damage in AlGaN/GaN HEMTs induced by reverse bias testing", IEEE Electron Device Letters, May 2009. [4] A. Chini et al., "Evaluation of GaN HEMT degradation by means of pulsed I-V, leakage and DLTS measurements", IET Electronics Letters, Apr. 2009.

THURSDAY PM

Session AA: Oxide Defects, Localized States, and Nanostructures

Thursday PM Room: 141
June 24, 2010 Location: University of Notre Dame

Session Chairs: Holger von Wenckstern, Univ Leipzig; Martin Allen, Univ Canterbury

1:30 PM

AA1, Vacancy Defect and Defect Cluster Energetics in Ion-Implanted ZnO: *Leonard Brillson*[1]; Yufeng Dong[1]; Filip Tuomisto[2]; Andrej Kuznetsov[3]; Bengt Svensson[3]; [1]Ohio State University; [2]Aalto University; [3]University of Oslo

Despite nearly sixty years of research, several fundamental issues surrounding ZnO remain unresolved. Chief among these have been the difficulty of p-type doping and the role of compensating native defects. Oxygen vacancies (V_O), V_O complexes, Zn interstitial-related complexes, and residual impurities such as hydrogen and aluminum are all believed to be donors in ZnO, while Zn vacancies (V_Zn) and their complexes are considered to be acceptors. Although their impact on carrier compensation is recognized, the physical nature of the donors and acceptors dominating carrier densities in ZnO is unresolved. It remains a challenge to correlate the commonly observed 1.9-2.1 eV "red" and 2.3-2.5 eV "green" luminescence emissions with specific native defects. Previous optical absorption, photoluminescence, electron paramagnetic resonance, and depth-resolved cathodoluminescence spectroscopy (DRCLS) studies indicate a correlation between the "green" optical transition and O vacancies (V_O).[1] Still controversial, however, is how such visible emissions correlate with the energetics of Zn/O vacancies, interstitials, and their complexes overall. This work clearly identifies the physical nature of the defects dominating optical features of this widely studied semiconductor and, in turn, these defects provide a consistent explanation for ZnO's effective free carrier densities on a local scale.[2] We have used depth-resolved cathodoluminescence, positron annihilation, and surface photovoltage spectroscopies to determine the energy levels of Zn vacancies and vacancy clusters in bulk ZnO crystals. Here we augment the depth-resolved luminescence of energy level transitions involving native defects with recent positron annihilation spectroscopy (PAS) results to determine the energetics of V_Zn and their complexes in ZnO over both surface

and near surface regions (7~1500 nm) in ion (Li or N) implanted and annealed bulk ZnO. The correspondence between these PAS native defect distributions and the DRCLS intensity distributions versus depth permits us to identify the luminescence energy associated with isolated VZn defects (~1.6 eV) as well as the energy shift due to vacancy cluster (1.9~2.1 eV) formation. Surface photovoltage spectroscopy (SPS) yields the positions of these levels with respect to the ZnO band edges. We associate the remaining deep level DRCLS emission (2.3~2.5 eV) with positively charged V_O-related defects, which are not detected by PAS, and describe how the balance between these donor and acceptor defects accounts for depth-dependent resistivity in these irradiated crystals. Taking these depth-resolved techniques altogether, we clearly identify the optical transitions and energies of V_Zn and vacancy clusters, the effects of different annealing methods on their spatial distributions in ion-implanted ZnO, and the contribution of V_Zn and V_O to near-surface resistivity. [1] L. J. Brillson et al., Appl. Phys. Lett. 90, 102116 (2007). [2] Y. Dong et al., Phys. Rev. B 81, R081201 (2010).

1:50 PM

AA2, O-H-Li-Complex in Hydrothermally Grown Single Crystalline ZnO: *Klaus Magnus Johansen*[1]; Hallvard Haug[1]; Pekka Tapio Neuvonen[1]; Knut Erik Knutsen[1]; Lasse Vines[1]; Edouard V Monakhov[1]; Andrej Yu. Kutnetsov[1]; Bengt Gunnar Svensson[1]; [1]University of Oslo

Results from Fourier Transform Infrared Spectroscopy (FTIR) and Secondary Ion Mass Spectrometry (SIMS) have been correlated to investigate the nature of the 3577 cm^{-1} local vibrational mode in four different hydrothermally grown ZnO wafers. This mode has previously been identified as the local vibrational mode of OH$^-$ adjacent to Li on Zn-site [1], also referred to as the O-H-Li-complex. In this work we show that the integrated absorption of the 3577 cm^{-1} band does in fact not follow the variation in the total Li-concentration between the different wafers. Rather, it turns out that the strength of the band is correlated with the presence of non-homogenously distributed Li along the c-axis, as revealed by SIMS. Interestingly, the Li-distribution is reproduced in the lateral directions, as if Li is decorating an underlying structure of basal plane defects. This indicates that the 3577 cm^{-1} is only observed when there is a presence of basal plane defects in addition to Li and H.

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AA3, Induced Gap States at Zinc Oxide Surfaces and Interfaces: M.W. Allen[1]; J.G. Partridge[1]; D.H.-S. Kim[1]; *S.M. Durbin*[1]; [1]University of Canterbury

There has been considerable progress in our understanding of defects and doping in ZnO, despite the fact that the various preparation techniques (molecular beam epitaxy, sputtering, pulsed laser deposition, as well as bulk techniques such as hydrothermal and pressurized melt) yield considerably different material in terms of optical and electronic characteristics. Still, many open questions remain about surface and bulk defects, as well as doping limitations in this material. Metal-semiconductor junctions provide an interesting window into fundamental characteristics of a semiconductor, especially when high quality rectifying (Schottky) junctions can be realized. Beyond enabling transient techniques such as DLTS, even the basic properties of the junction and its formation create a probe for interface states which are often intimately related to bulk defect levels. However, practical aspects of fabricating Schottky contacts, such as lateral inhomogeneity, contaminants, and defects, can complicate the comparison of experimentally obtained barrier heights to theoretical predictions and extraction of information about intrinsic properties. The diode ideality factor η (which should approach unity for laterally homogeneous interfaces, after accounting for image force effects) is also strongly affected by the same issues, and correlations can be observed between barrier height and η when measuring large numbers of devices. Intriguingly, ZnO could prove to be an interesting test case for evaluating various theoretical Schottky contact formation models, as it is significantly more ionic than most semiconductors, resulting in weaker Fermi pinning due to interface states. ZnO also does not require the removal of a native oxide layer for device processing, thereby avoiding often aggressive cleaning procedures which can roughen or otherwise damage the surface. We have fabricated arrays of rectifying metal-ZnO contacts using bulk wafers and a wide variety of metals, using an eclipse pulsed laser deposition technique which

results in large barrier heights (typically > 0.8 eV) and low η (approaching the image force limit). Using the electrical characteristics of these near-ideal diodes, we evaluate both Tung's chemical bonding and Moench's metal induced gap states + electronegativity models. The lack of agreement with either of these popular models raises several questions, including whether predictions for the branch point energy in ZnO — a key parameter of induced gap states relevant to discussions of heterointerfaces as well as doping ability and gap states — are accurate. This work was supported in part by Marsden Fund grant UOC0604, the MacDiarmid Institute for Advanced Materials and Nanotechnology, and the University of Canterbury.

2:30 PM

AA4, Optical Properties of Gd Implanted ZnO Single Crystals: *John Kennedy*[1]; Peter Murmu[1]; Andreas Markwitz[1]; Ben Ruck[2]; Ruben Mendelsberg[3]; Roger Reeves[4]; P Malar[5]; Thomas Osipowicz[5]; [1]GNS Science; [2]Victoria University of Wellington; [3]The MacDiarmid Institute of Advanced Materials and Nanotechnology; [4]University of Canterbury,; [5]National University of Singapore

Rare earth (RE) elements doped Zinc oxide (ZnO) is being investigated intensively for spintronics applications. RE elements (e.g. Eu, Er, Tm and Gd) have been reported to create optical centres, and room temperature ferromagnetism in ZnO. The study of doping effects along with intrinsic defects in ZnO is of particular interest for better understanding of altered electronic structure which eventually modifies the optical and magnetic properties of the material. We present the results from a study of unimplanted and Gd implanted ZnO (0001) single crystals with fluences ranging from 4.6x1014 to 1.1x1016 Gd ions per square centimetre at an energy of 30 keV. The corresponding Gd atomic concentrations varied from 0.5 to 8.4 % per formulae unit. Average implantation depths were 10 to 12 nm and the maximum depth ranged from 20 to 25 nm. The implanted samples were subsequently annealed in a vacuum for 30 minutes at 650 and 750 ☐C. Rutherford backscattering and channeling techniques were employed to analyse the crystalline quality, damage recovery and Gd lattice site location. It was found that most of the Gd ions are incorporated into substitutional sites after the implantation. Photoluminescence (PL) of unimplanted ZnO shows the enhanced green emission on vacuum annealing along with typical UV emission at 5K. Most likely oxygen vacancies (VO), created by desorption of oxygen during vacuum annealing, could be origin of green luminescence. UV emission is due to recombination of an exciton bound to a neutral donor and its intensity is reduced in the Gd implanted samples due to structural degradation. Orange light emission is observed in place of green, which suggests the oxygen vacancies are compensated most likely by implanted Gd ions which in turn reduce the green emission. However, the exact origin of the orange emission is not known at present. Detailed results from structural, morphological and optical measurements will be presented at the conference.

2:50 PM

AA5, High-Resolution Laplace DLTS on Mg$_x$Zn$_{1-x}$O PLD Thin Films: *Holger von Wenckstern*[1]; Florian Schmidt[1]; Kerstin Brachwitz[1]; Matthias Schmidt[1]; Christof Dietrich[1]; Marius Grundmann[1]; [1]Universität Leipzig

The increasing interest in wide bandgap semiconductors puts, besides GaN-based material, ZnO and its alloys in the focus of semiconductor research. Potential applications are, e.g., UV optoelectronics, front contacts of solar cells, transparent transistors and HEMTs. For all these applications a profound knowledge of deep level defects in ZnO and related alloys is necessary for optimization of performance. Electrical investigations like deep level transient spectroscopy (DLTS) of binary ZnO revealed that the so-called E3 defect, having thermal activation energy E_t of 300 meV and an apparent capture cross-section σ_{app} of 2 $\times$ 10^{-16} cm^2, is incorporated independent of the growth method. Laplace deep level transient spectroscopy (LDLTS) showed that a defect called E3' with similar emission rate as the E3 defect may also exist in bulk ZnO and thin films [1]; the separation of E3 and E3' is usually not possible with DLTS. For ZnO-based alloys such as MgZnO and CdZnO, having higher and lower bandgap than ZnO, respectively; very little data about defects exist. Only a recent study provides E_t and σ_{app} of E3 in Mg$_x$Zn$_{1-x}$O for x < 0.09 determined by thermal admittance spectroscopy (TAS) and DLTS [2]. In this contribution we will report TAS, DLTS and LDLTS measurements on Mg$_x$Zn$_{1-x}$O thin films with x < 0.05 to provide first comprehensive data on the incorporation of E3 and E3' in this ZnO-based alloy. We used ZnO and Mg$_x$Zn$_{1-x}$O thin films grown by pulsed-laser deposition on a-plane sapphire substrates. For all samples a 200 nm thick degenerately conducting ZnO:Al layer was deposited prior to the main layer to be used as Ohmic back contact of the diodes. Circular Schottky contacts were realized by reactive sputtering of Pd. All samples exhibit high rectification and low series resistance and are suited for TAS, DLTS and LDLTS. We demonstrate that defect parameters obtained from conventional DLTS are often erroneous for samples containing both the E3 and the E3' defect due to their similar emission rates. We provide means to conclude on the existence of the E3' defect in a particular sample by acquiring DLTS signals for different filling pulse lengths. Nevertheless, the electrical parameters of E3 and E3' may only be unambiguously determined by LDLTS. The LDLTS measurements on Mg$_x$Zn$_{1-x}$O thin films clearly show the incorporation of both E3 and E3' for low Mg-contents x &le 0.005. However, we do not observe E3' in samples with x &ge 0.009. This result could help to understand the higher reproducibility of Mg$_x$Zn$_{1-x}$O compared to ZnO MESFETs [3]. [1] Auret *et al.*, Physica B **401-402**, 378 (2007). [2] von Wenckstern *et al.*, J. Electron. Mater. (available online, DOI: 10.1007/s11664-009-0967-0). [3] Grundmann *et al.*, Mat. Res. Soc. Symp. Proc. **1201** (2010), in press.

3:10 PM Break

3:30 PM Student

AA6, Observation of a Strong Polarization Induced Quantum-Confined Stark Effect in Mg$_x$Zn$_{1-x}$O/ZnO Quantum Wells: *Matthias Brandt*[1]; Holger von Wenckstern[1]; Marko Stölzel[1]; Alexander Müller[1]; Gabriele Benndorf[1]; Martin Lange[1]; Jan Zippel[1]; Jörg Lenzner[1]; Christof Dietrich[1]; Michael Lorenz[1]; Marius Grundmann[1]; [1]Universitaet Leipzig

The quantum-confined Stark effect (QCSE) has been observed for samples grown by molecular beam epitaxy (MBE) containing a Mg$_x$Zn$_{1-x}$O/ZnO quantum well (QW)[1]. For the occurrence of the QCSE a difference in the electric polarization at the heterointerfaces, a significantly large QW width and abrupt interfaces are required. Quantum confinement effects in Mg$_x$Zn$_{1-x}$O/ZnO QWs grown by pulsed laser deposition (PLD) were previously observed[2]. However, even for high QW widths no significant influence of the QCSE on the 2K luminescence was detected in these experiments. Similar results are reported by numerous authors for PLD grown Mg$_x$Zn$_{1-x}$O/ZnO QWs[3]. In the experimental study reported here, the laser fluence in the PLD process was controlled in order to modify the energy of the particles in the laser plasma. This had a tremendous influence on the sharpness of the heterointerfaces. For an adequate choice of the laser fluence a systematic redshift of the QW luminescence with increasing well width of up to 230 meV below the emission of the free exciton in bulk ZnO was observed. Additionally, due to the decreased overlap of the electron and hole wave-functions the transition probability is reduced. An increase in the exciton lifetime up to 0.3ms is observed. Values previously reported for MBE grown samples[1], showing very high quality QW interfaces, are quantitatively different, with the longer decay time for a given red-shift in the PLD QWs. Mg$_x$Zn$_{1-x}$O/ZnO heterostructures were grown by pulsed laser deposition (PLD) on a-plane sapphire and ZnO substrates. Mg$_x$Zn$_{1-x}$O grows pseudomorphically on ZnO substrates, leading to perfectly organized vicinal surfaces[4]. Pendellösung-oscillations were observed in high resolution X-ray diffraction, confirming the sharpness of the interfaces. A systematic linear dependence of the c-axis lattice constant on the Mg content in the barrier layer is seen for the samples grown on ZnO. The relation was explained by classical elastic theory, as well as similar data obtained on films grown by MBE[5]. In order to cover a large number of different thicknesses, wedge-shaped QWs were grown by leaving off substrate rotation during growth. Crystallizing in the wurtzite structure, both ZnO and Mg$_x$Zn$_{1-x}$O possess a spontaneous polarization. Upon the formation of a heterostructure an additional piezoelectric polarization component is introduced, increasing or diminishing the polarization. The difference in the spontaneous polarization in adjacent ZnO and Mg$_x$Zn$_{1-x}$O layers and its dependence on the Mg content x can be estimated from the thickness dependence of the transition energy and the exciton lifetime in the QW.

3:50 PM

AA7, Low Temperature Electrochemical Growth of ZnO Nanobelts, Nanowalls, Nanospikes and Nanowires: Growth Mechanism and Field Emission Study: *Debabrata Pradhan*[1]; Kam Leung[1]; [1]University of Waterloo

ZnO nanostructures are promising materials with a potential for several applications such as in the photonics, opto-electronics, electron field emissions and solar cells. In the present work, we deposited both the two-dimensional (i.e. nanowalls and nanobelts) and one-dimensional (i.e. nanospikes and nanowires) ZnO nanostructures on inexpensive conducting glass and plastic substrate using a facile electrochemical deposition technique. All the electrodeposition experiments were performed below 70°C. The electrolyte concentration, deposition temperature and deposition potential were found to significantly control the morphology of ZnO nanostructures. Glancing angle X-ray diffraction and transmission electron microscopy were used to obtain the crystallinity and growth direction of different ZnO nanostructures. Energy dispersive X-ray analysis and depth profiling X-ray photoelectron spectroscopy were used to measure the composition of as-synthesized materials, which suggested the cause for different nanostructure formation. In particular, Cl^- ions capping on the preferred [0001] growth direction of ZnO under fast hydroxylation kinetics condition observed at a higher $Zn(NO_3)_2.6H_2O$ electrolyte concentration (>0.05 M). The electron field emission measurement showed higher emission current density at a lower electric field from the nanospikes as compared to that of the nanowalls. This is attributed to the tapered tips of the nanospikes geometry which concentrates a higher electric field in comparison to the nanometer thick ledge of nanowalls. The nanospikes showed a turn-on electric field of 3.2 V/μm for 1 μA/cm^2 and threshold field of 6.6 V/μm for 1.0 mA/cm^2. This superior field emission property makes the nanospikes to be one of the best ZnO field emitter fabricated on a glass substrate at low temperature.

4:10 PM Student

AA8, Synthesis and Field Emission Characterizations of Well-Aligned Single-Crystal Al-Doped ZnO Nanowires Grown at Low Temperature: *Po-Yu Yang*[1]; Jyh-Liang Wang[2]; Wei-Chih Tsai[3]; Der-Ming Kuo[3]; Hau-Yuan Huang[3]; I-Che Lee[1]; Chia-Tsung Chang[1]; Sih-Yin Wang[4]; Shui-Jinn Wang[3]; Huang-Chung Cheng[1]; [1]National Chiao Tung University; [2]Ming Chi University of Technology; [3]National Cheng Kung University; [4]Chang Jung Christian University

ZnO nanowires (NWs) have attracted considerable interests as field emitters because of thermal stability, chemical stability, and high mechanical strength.1-3 Recently, the ZnO nanostructures are doped with group III metal elements, such as Al, In, and Ga, which can increase their electrical properties. To data, the low-temperature fabrications of Al-doped ZnO (AZO) NWs arrays and according field emission (FE) properties have not been reported yet. Therefore, the hydrothermal method was proposed to synthesis the pure ZnO and AZO NWs on glass substrates at a relatively low temperature, i.e. 85 °C. In this work, the optical, physical, and field emission characteristics of the low-temperature pure ZnO and AZO NWs with various dopant concentrations were systematically addressed. In experiments, a 200 nm-thick AZO film was sputtered on glass substrates to serve as a seed layer for the growth of pure ZnO and AZO NWs. The precursor solution containing zinc nitrate hexahydrate (Zn (NO3)2□6H2O, 2.5 mmol), hexamethylenetetramine (HMTA, 2.5 mmol) and distilled water. The aluminum nitrate nonahydrate (Al (NO3)3□9H2O) powders were used as the doping source to add in the precursor solution. Then the samples were placed in the mixed solution at 85 °C for 1 hour in a regular laboratory oven on a hot plate. After hydrothermal growth method growth, the samples were washed in DI water and dried in air. The FE-SEM images of the pure and AZO NW arrays growth were performed on the AZO/glass substrate. Both the Al-doped and undoped ZnO nanowires are well ordered and vertically aligned with controllable length (~1 μm) were obtained on the substrate. The near band-edge (NBE) emission peaks of pure ZnO and AZO NWs shift from 380 nm to 372 nm as the concentration of Al increases. This phenomenon was reported as blue-shift in emission peak and can be connected to Burstein–Moss effect because of the presence of the doped Al in the NWs. The FE characteristics of the pure ZnO and AZO NWs arrays with different Al-atomic concentration grown on AZO/glass substrates. The FE characteristics of AZO NWs arrays demonstrated the higher current density, lower turn-on field and lower threshold field, compared with that of pure ZnO NWs arrays. It suggests that the field emission characters of the ZnO NWs are noticeably improved with Al-doping and proportional to Al-doping amount. In short, a low-temperature hydrothermal growth method which is simple and easy to scale-up has been employed to synthesize the well-aligned arrays of AZO NWs with superior field emission characteristics, implying the potential for fabricating flexible optoelectronic and field emission devices.

4:30 PM Student

AA9, Correlation of ZnO Polar Surface Nanostructure with Native Point Defects: *Tyler Merz*[1]; Daniel Doutt[1]; Leonard Brillson[1]; [1]The Ohio State University

We used a complement of nanoscale depth-resolved cathodoluminescence spectroscopy (DRCLS), atomic force microscopy (AFM), Kelvin-probe force microscopy (KPFM), and surface photovoltage spectroscopy (SPS) to identify how surface morphology, nanostructure, and polarity of ZnO surfaces correlate with electronically-active native point defects. ZnO is a promising optoelectronic semiconductor with a striking ability to grow nanostructures, but its electronic surface and interface states are not well understood despite their impact on transport and recombination. Previous near-surface DRCLS showed that nanoscale asperities on bare ZnO surfaces exposed to ambient atmosphere for several months can have high trapped charge densities that dramatically increase free carrier recombination and band bending [1]. Not only do surface morphology and recombination velocity correlate within the outer tens of nanometers, but they associate with specific native point defects. SPS measures the filling and emptying of these states and thereby their energy level position in the band gap. In turn, CLS associates these optical transitions with oxygen and zinc vacancies, VO and VZn, respectively. Positron annihilation spectroscopy (PAS) showed that 2.1eV DRCLS emission correlates with VZn vs. depth, anticorrelating with 2.5 eV VO emission [2]. Furthermore, our KPFM-based SPS allowed us to correlate DRCLS optical emissions with optical filling and emptying transitions of the same near-surface regions across ZnO surfaces on a nanometer scale. These localized measurements also reveal Zn vacancy concentrations that increase with proximity to the most common nanostructures - nanorods, nanoclumps, step edges, and starburst patterns. These defects in fact play a role in spontaneous growth of nanoscale surface features. SPS spectra (fig. 1) display evidence for VZn charge emptying within fields of nano-"bumps" but not in flat ZnO surface areas. Near individual nanobumps, 2.1eV trap densities increase with proximity (fig.2) as do 2.1 eV vs. band gap nano-CLS spectra emissions. SEM-imaged hexagonal nano-pits display 2.1 eV intensities on the ZnO (0001) surface showing that growth of nanoscale features is mediated by the creation of sub-surface Zn vacancies as free surface Zn oxidizes. Furthermore, KPFM maps (fig. 3) before (a) vs. after (b) 2.25 eV illumination show increased potential that reveals large concentrations of VZn distributed non-uniformly around and extending away from AFM pit features. Low (<1 keV) electron beam energy DRCLS spectra and probe depths < 25nm show different deep level emissions dominating (fig.4) for the two polar surfaces. VZn emission dominates the Zn (0001) face while VO dominates O (000-1) spectra. These polarity affects manifest themselves not only in DRCLS but in potential maps and surface morphology as well. Our findings demonstrate the importance of polar effects in forming the surface and near-surface defects that in turn control the spontaneous formation of nanoscale asperities on ZnO surfaces.

4:50 PM Student

AA10, Evolution and Growth of Nanostructures on ZnO with Staged Annealing: *Daniel Doutt*[1]; Tyler Merz[1]; Leonard Brillson[1]; [1]The Ohio State University

We used atomic force microscopy (AFM), Kelvin probe force microscopy (KPFM), and surface photovoltage spectroscopy (SPS) to establish how nanostructures grow on polar ZnO surfaces. We have already shown that nanostructures grow spontaneously on ZnO surfaces with prolonged air exposure. These observations suggest that ZnO nanostructures grow by oxidation of Zn at the free ZnO surface and the extraction of Zn atoms from the underlying lattice. In order to explore the thermodynamics of this process, we have measured the

morphology, electric potential, and defect distributions of ZnO surfaces as a function of annealing temperature in flowing oxygen over a 400 ºC temperature range. These measurements reveal dramatic changes in surface morphology for both the Zn and O polar surfaces, the evolution of crystallographically oriented patterns with increasing temperature. These results confirm the pivotal role of ambient oxygen in the ZnO surface growth processes and reveal a characteristic activation energy that is consistent with theoretical predictions for Zn interstitial diffusion. AFM and KPFM maps (fig. 1) show the changes in surface morphology and contact potential with respect to temperature and gas exposure for representative 10x10 um areas of the same Zn (0001) surface. Deep (~150 nm) well defined hexagonal pits are seen on the room temperature and annealed surfaces with spoke-like trenches extending away from the corners and faces of hexagonal pits and trenches. Both these pits and the trenches show pronounced (> 50 mV) potential increases that increase further with annealing temperature. Conversely, O-polar (000-1) surfaces (fig. 2) initially show similar patterns with only light pitting, no well-defined geometry, and raised spokes extending from the edges of pits. After a 200 ºC anneal, this pitting increases with strong (~150 mV) negative potentials associated with pits and spokes. At 300ºC we see a dramatic growth of nanoscale "bumps" ranging from ~ 5 – 50 nm in height and further potential change. After the 300 ºC anneal, the difference in KPFM maps of the surface in the dark vs. after 2.25 eV illumination, i.e., optical transitions that empty VZn defect levels and reduce band bending [2], highlight the pronounced nonuniformities of these VZn potential variations.From the AFM increase in nanorod mass vs. temperature, Arrhenius plots of the oxygen face yield an activation energy of ˜150+10 meV. This low value suggests that the ZnO nanostructure growth occurs by Zn interstitial diffusion. Indeed, Zn interstitials are calculated to be fast diffusers with migration barriers of 0.57 eV [1]. The characteristic patterns of rays or trenches extending away from nanofeatures appear to align with crystallographic directions and suggest preferential pathways with lower migration barriers than in the bulk. Thus, coupled AFM, KPFM, and SPS appears to opens up a new avenue for studying nanostructures.

Session BB: III-V Novel Electronic Devices

Thursday PM
June 24, 2010

Room: 155
Location: University of Notre Dame

Session Chairs: Andrew Allerman, Sandia National Laboratories; Michael Manfra, Purdue University

1:30 PM Student
BB1, Demonstration and Room Temperature Electrical Characteristics of a Nitride Hot Electron Transistor with GaN Base of 10 nm: *Sansaptak Dasgupta*[1]; Nidhi Nidhi[1]; A. Raman[1]; J. S. Speck[2]; Umesh Mishra[1]; [1]ECE Dept. UCSB; [2]Materials Department, UCSB

A Hot Electron Transistor (HET) works on the principle of injection of 'hot' electrons above a barrier into a transit region (base), where they travel with minimal scattering and are collected in the collector. It is thus possible to obtain near ballistic transport in these devices, larger current drives and operation at frequencies higher than conventional (diffusive transport) transistors. In this work, we report on GaN based unipolar HETs which show room temperature operation. The device structure consists of 40 nm of AlGaN (24%) Si doped 1×10^{18} cm^{-3}, a 10 nm GaN base doped 1×10^{19} cm^{-3} and a 7% AlGaN collector doped 7×10^{17} cm^{-3}. The epilayer is grown by PAMBE on GaN (0001) templates. The device is fabricated by etching the emitter mesa to the base and then etching the base down to the collector contact layer, and subsequent depostion of ohmic metal stack of Al/Au. The Base-Emitter diode and base-collector diodes which are isotype N-n junctions have been characterized and they show thermionic emission characteristics at forward bias. Common base measurements demonstrate an α of ~ 0.97 which is commensurate with a β of 35 - 40. Peaks due to quasi ballistic transport of hot electrons which are injected into the base are observed in conductance measurements (δIc δVcb). Device analysis and effect of different e-b and b-c barriers would be discussed.

1:50 PM Student
BB2, Novel Cs-Free GaN Photocathodes: Neeraj Tripathi[1]; L. Bell[2]; Shouleh Nikzad[2]; Mihir Tungare[1]; Puneet Suvarna[1]; Ryan Vinson[1]; *Fatemeh (Shadi) Shahedipour-Sandvik*[1]; [1]University at Albany, State University of New York; [2]Jet Propulsion Laboratory, California Institute of Technology

GaN and AlGaN based photocathodes have attracted considerable attention for their application in image intensifiers, astronomy and UV detection and emission systems. Small electron affinity of AlGaN alloy allows development of high quantum efficiency negative electron affinity (NEA) photocathodes with significant advantages such as solar blindness, radiation hardness and low noise. Conventional photocathodes achieve NEA by cesiating the photocathode surface. Fabrication, optimization, and installation in vacuum is required for cesiated photocathodes due to the high chemical activity of the Cesium. Such requirement increases cost and limits the range of potential applications. Further, such photocathodes have been reported to suffer from chemical instability and degradation with time. Here we report on a novel Cs-free GaN based photocathode that utilizes band engineering near the photocathode surface to achieve permanent NEA. Device structure is composed of a Mg doped GaN template grown on sapphire, followed by Si-delta doping and a thin n+GaN cap. By placing a Si delta doped layer on the Mg doped GaN surface conduction band of the overall structure is pulled close to the Fermi level of the p-GaN. A thin n+GaN cap is deposited to provide stability to the Si-delta doped layer. Device design parameters including Si-delta doping and thickness of n+GaN cap layers play a critical role in determining the emission threshold and quantum efficiency of the device. Further, polarization induced charges at the device surface influence the device characteristics. We have performed physics based simulations to optimize the device design parameters taking into account polarization induced surface charges. Device structures have then been epitaxially grown using a Veeco D180 MOCVD system and characterized using secondary ion mass spectroscopy (SIMS) and photoemission (PE) measurements. A series of growth experiments with varying conditions have been performed to optimize Si incorporation in the delta doped layer and quality and thickness of the n+GaN cap layer. Emission threshold of the device has been observed to increase with increase in the n+GaN cap thickness. Such behavior has been successfully modeled and is attributed to local electric fields caused by the negative polarization induced surface charges. Quantum efficiency of the device follows systematic exponential decay with increase in n+GaN cap thickness. Increase in Si incorporation in the delta doped layer, up to the optimum value, has shown to improve device characteristics. Further increase in Si incorporation caused increase in emission threshold and degradation of the photocathode surface. Results of our simulation and experimental work including device growth, optimization and characterization will be discussed.

2:10 PM
BB3, Influence of MOVPE Growth Conditions on Intersubband Absorption in AlN –AlGaN Superlattices: *Andrew Allerman*[1]; Jonathan Wierer[1]; Qiming Li[1]; Mary Crawford[1]; Stephen Lee[1]; [1]Sandia National Laboratories

The large conduction band offset (~ 2 eV) in AlN and GaN heterostructures, along with rapid (< 1ps) intersubband (ISB) transitions between confined states drives interest in utilizing AlN-GaN superlattices for ultra-fast, optical switches (~1 Tb/s) and electro-optical modulators operating at telecom wavelengths (λ = 1.55 μm). Optical ISB absorption in nitride quantum wells has been previously observed down to 1.08 μm with absorption recovery times of 150-400 fs. To date, structures grown by molecular beam epitaxy have exhibited ISB absorption at the shortest wavelengths with the narrowest line-width, indicative of monolayer abrupt interfaces. Growth of similar structures by metal-organic vapor phase epitaxy (MOVPE) has resulted in ISB absorption at longer wavelengths with broader line-widths. The lower performance of structures grown by MOVPE has been attributed to interface roughness and thickness fluctuations due to the higher growth temperatures typically employed. Recently, Yang *et. al.* have reported ISB absorption peaked at 1.52 μm in MOVPE structures grown at significantly lower growth temperatures (830°C) where the wells were grown by means of a pulsed-growth approach to increase the electron concentration. In this work, we investigate the effect of MOVPE growth conditions on the performance of AlN-AlGaN superlattices designed to exhibit ISB transitions in

the near infrared without the need for pulsed growth approaches. Superlattices consisting of 20 periods of AlN barriers (~ 52Å) and $Al_{0.10}Ga_{0.90}N$ wells (10-15 Å) were grown conventionally, without pulsing, on 2.8 μm thick AlN films on sapphire. Wells were doped with Si at levels that achieved electron concentrations of $5x10^{19}$ or $1x10^{20}$ cm^{-3} in separate calibration growths. Optical absorption was measured by Fourier transform infrared spectroscopy on samples that are 5-8 mm wide with facets polished at ~45°. A significant shift in absorption to shorter wavelengths and narrower linewidths was observed in samples grown at lower growth temperatures suggesting improved interface abruptness. Absorption was peaked at 1.64 μm with a FWHM of 130 meV in a sample grown at the lowest temperature investigated, 760°C. Omega-2theta x-ray diffraction (XRD) scans about the (0002) reflection of samples grown at lower temperatures (885-760°C) showed additional higher-order satellite peaks that were not observed in samples grown at high temperature (1010°C). TEM images confirm improvement in interface abruptness in ISB structures grown at lower temperatures. AFM images reveal step-flow growth in all samples; however, pits and more complex structures appear at step edges in samples grown at 930°C and lower. Relationships between growth conditions, interface abruptness and ISB absorption will be discussed. 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.

2:30 PM Student

BB4, Engineering Ferromagnetism in Gd-Doped GaN Two-Dimensional Electron Gases: *Jing Yang*[1]; D. Hoy[1]; S. Carnevale[1]; E. Uchaker[1]; R. Myers[1]; [1]Ohio State University

In ferromagnetic semiconductors, the magnetization and spin polarization can be controlled with an electric field. These properties could be utilized in proposed spin-transistors in which, besides traditional charge gain, spin inputs and outputs could be electrically controlled and amplified. Such a device would exhibit low power switching and offer a spin functional platform for novel logic and memory devices. While hole-mediated ferromagnetism in GaMnAs is well established, after more than a decade of intensive work it exhibits low Curie temperatures (~170K) and requires unpractical electric fields to control the ferromagnetism. There are countless reports of above room temperature ferromagnetism in magnetically-doped wide band gap semiconductors, including bulk $Ga_{1-x}Gd_xN$. Unfortunately for these materials, evidence of a coupling between the electronic structure of the host semiconductor and the ferromagnetic phase is lacking. Here we utilize confinement and polarization engineering to explore magnetic coupling between Gd-ions and electron spins in AlN/GaN two dimensional electron gases (2DEGs) grown by plasma-assisted molecular bean epitaxy. Such 2DEGs might enable an n-type ferromagnetic semiconductor heterostructure that could be easily controlled with a gate bias. Structural characterization by SIMS, AFM, and HRXRD is used to study the incorporation of Gd in GaN by both δ-doping and statistical doping and to test for second phase precipitates, such as rock salt GdN. Using SQUID and Hall effect measurements, we examine the dependence of the magnetic and electronic properties as a function of the distance (d) between δ-doped Gd (~10^{14}cm^{-2}) region and the AlN/GaN interface which is adjacent to the high density electron sheet (~10^{13}cm^{-2}). Initial structures exhibit ferromagnetism, but additional optical and electronic measurements are needed to determine if the observed ferromagnetism is coupled to the electronic structure of the 2DEG.

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BB5, Nearly Ideal Current-Voltage Characteristics of Schottky Barrier Diodes Directly Formed on GaN Free-Standing Substrates: *Jun Suda*[1]; Kazuki Yamaji[1]; Yuichirou Hayashi[1]; Tsunenobu Kimoto[1]; Kenji Shimoyama[2]; Hideo Namita[3]; Satoru Nagao[3]; [1]Kyoto University; [2]Mitsubishi Chemical Corporation; [3]Mitsubishi Chemical Group Science and Technology Research Center, Inc

GaN-based electronic devices have attracted much attention due to its potential for low on-resistance and high operation temperature. At present, these devices are fabricated by using epitaxial layers. On the other hand, most of Si electronic devices are directly formed on Si substrate without epitaxial growth process.

Recently, high-quality GaN free-standing substrates are available by various methods. It is important to assess the possibility of GaN-based electronic devices directly formed on GaN substrates. In this study, we fabricated Schottky barrier diodes directly on hydride vapor phase epitaxy (HVPE)-grown GaN free-standing substrates. Substrates with different donor concentrations ranging from $1x10^{16}$ to $2x10^{17}$ cm^{-3} were prepared. The threading-dislocation densities (TDD) of these substrates were estimated to be $3x10^6$ cm^{-2} by cathodoluminescence mapping. After formation of backside Ohmic contacts by Ti/Al, Ni Schottky contacts were formed by physical evaporation directly on chemical mechanical polished (CMP) GaN surfaces. The diameter of electrode is 100-300 μm. Current-voltage (I-V) characteristics and capacitance-voltage (C-V) characteristics were measured at room temperature. We have measured 10-50 diodes for each substrate. A small number of diodes exhibited leaky characteristics. We excluded these diodes from the following analysis, since these diodes may contain macroscopic defects originating from substrate itself or device processing. The diodes showed ideal forward I-V characteristics. The I-V curves were well fitted by the formula ($I=I_0\{\exp(eV/nkT)-1\}$) with series resistance. Ideality factors (n) of the diodes were 1.02-1.03 for all substrate. Barrier heights of these diodes were estimated to be 0.93 eV from I_0. Almost identical barrier heights were obtained from built-in potential of $1/C^2$-V plots. The doping range investigated is rather high. In the case, thermionic field emission (TFE) instead of simple thermionic emission (TE) should be considered. We calculated reverse I-V characteristics by TFE theory with values of barrier height and accurate doping concentration obtained from forward I-V and C-V characteristics. Measured reverse I-V characteristics showed excellent agreement with the calculations. The agreement was observed for all diodes with the doping range investigated. As a reference, we also fabricated Schottky diodes on GaN heteroepitaxial layers grown on sapphire substrates by metalorganic vapor phase epitaxy (MOVPE). The TDD of layers was 10^9 cm^{-2}. The diodes exhibited good forward characteristics. However, for reverse bias, measured currents were four orders of magnitude larger than that predicted from TFE theory. Reverse leakage is severely affected by high-density threading dislocations in the MOVPE-grown GaN diodes. These results indicate that surface damaged layer due to CMP process and leakage current due to threading dislocations ($3x10^6$ cm^{-2}) are negligible for Schottky diodes directly fabricated on HVPE-grown GaN substrates with doping range of $1x10^{16}$ to $2x10^{17}$ cm^{-3}. Our results show that CMP-processed HVPE-grown GaN substrates have a potential for electronic device fabrication.

3:10 PM Break

Session CC: III-N HEMTs II

Thursday PM   Room: 155
June 24, 2010   Location: University of Notre Dame

Session Chairs: Andrew Allerman, Sandia National Laboratories; Michael Manfra, Purdue University

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3:30 PM Student

CC1, High Al Composition $Al_{0.72}Ga_{0.28}N$/AlN/GaN Heterostructures with High Mobility Two-Dimensional Electron Gases: *Guowang Li*[1]; Yu Cao[1]; Huili Xing[1]; Debdeep Jena[1]; [1]University of Notre Dame

Low Al composition (<40 %) AlGaN high-electron mobility transistors (HEMTs) have been an excellent technology platform for both high power and high frequency applications. Deep sub-micrometer HEMTs with decreasing barrier thickness are required to further boost the device performance. For AlN barrier, low contact resistance comparable to AlGaN barrier is hampered by the wide band gap of AlN (6.2 eV). A high Al composition AlGaN barrier layer can provide a high 2-D electron-gas (2DEG) density, and allow AlGaN thickness scaling. However, few groups reported on the growth of high Al composition AlGaN/GaN HEMT structures and the room temperature (RT) electron mobility has been limited to 500 cm^2/Vs with Al composition higher than 70%. Molecular beam epitaxy (MBE) grown high Al composition AlGaN has been observed to

suffer spontaneous phase modulation. We report the study of 2DEG structures with high Al composition (>70%) AlGaN grown by plasma-assisted MBE. In metal-rich regime, with the Ga flux of $(1.1 - 1.3) \times 10^{-7}$ torr, Al flux of 4.3×10^{-8} torr, RF power of 275 W and thermocouple temperature ranging from 580 to 680°C, the epitaxial growth of relatively thick (>3 nm) high Al composition AlGaN directly on top of GaN always results in hexagonal stripes. The origin of the stripes is still under investigation, and we suspect it might be related to lateral phase separation. However, by inserting an ultrathin (<1 nm) AlN spacer, the surface morphology was dramatically modified and consisted of atomic steps. The growth rate and Al composition of the AlGaN layer were calibrated by high-resolution X-ray diffraction (XRD) measurement of a nine-period 2.7 nm/0.6 nm/26.7 nm $Al_{0.72}Ga_{0.28}N$ /AlN/GaN multiple quantum well calibration structure. The AlN spacer thickness was kept around 0.6 nm. The polarization-induced 2DEG density increases with total barrier thickness for samples with AlN spacer and 72% AlGaN. For HEMTs heterostructures with 3.9 nm/0.6 nm $Al_{0.72}Ga_{0.28}N$ /AlN barrier, at room temperature the 2DEG mobility reaches 1140 cm^2/Vs at a sheet density of 2.3×10^{13} cm^{-2}, which yields low sheet resistance of 238 /□. For the samples without AlN spacer the electron mobility is typically about 120 cm^2/Vs at room temperature and there was no clear increase at 77 K. In conclusion, we have succeeded in demonstrating high Al composition alloy AlGaN/GaN HEMT structures with high carrier mobility. An ultrathin AlN interlayer was crucial to suppress phase separation and yield high mobilities, paving the way for deep submicron HEMTs.

3:50 PM Student

CC2, Two-Dimensional Electron Gas in $In_xAl_{1-x}N$/Aln/GaN Heterostructure Field-Effect Transistors Depending on Indium Composition: *Suk Choi*[1]; Hee Jin Kim[1]; Zachary Lochner[1]; Bravishma Narayan[1]; Yun Zhang[1]; Shyh-Chiang Shen[1]; Jae-Hyun Ryou[1]; Russell Dupuis[1]; [1]Georgia Institute of Technology

AlGaN/GaN heterostructure have been successfully used for heterostructure field-effect transistors (HFETs) as high density two-dimensional electron gas (2DEG) can be generated effectively from their large lattice mismatch and high piezoelectric field. However, attempts to enhance device performance by increasing Al composition in AlGaN barrier layer have not been very successful, because large tensile strain caused by high Al composition leads to relaxation of barrier layer and low crystalline quality which reduces 2DEG density. To resolve this problem, use of nearly in-plane lattice-matched InAlN barrier with ~18% of In composition on top of GaN is proposed. Lattice-matching $In_{0.18}Al_{0.82}N$ barrier layer can minimize strain-induced layer quality depreciation while its higher spontaneous polarization field than $Al_{0.25}Ga_{0.75}N$ generates high density of 2DEG and high carrier mobility over AlGaN/GaN HFETs. In addition, strain and polarization field engineering is possible by controlling In composition of barrier layer. If the In composition in InAlN barrier layer is lower than 18%, tensile strain in the layer will produce piezoelectric field which is aligned in the same direction to spontaneous polarization field and threshold voltage will be negatively shifted. On the contrary, In composition higher than 18% in barrier layer will produce compressive strain and piezoelectric field which is antiparallel to spontaneous polarization field. As a result, piezoelectric polarization field and spontaneous polarization field compensate each other, and threshold voltage shifts toward positive direction. Therefore, InAlN/GaN HFET structure with appropriate In composition and compressively strained barrier layer is expected to exhibit enhancement mode operation with positive threshold voltage. In this study, we report novel method for 2DEG engineering to achieve enhancement mode operation of InAlN/GaN HFETs. InAlN/GaN heterostructures with high quality InAlN layer were grown by using metalorganic chemical vapor deposition (MOCVD) with various In composition from 18% to 25%. The threshold voltage of fabricated HFETs were measured to be -3V for HFETs with $In_{0.18}Al_{0.82}N$, -1.25V for $In_{0.22}Al_{0.78}N$, and -0.1V for $In_{0.25}Al_{0.75}N$. The fabricated device shows good feasibility for enhancement mode operation of InAlN/GaN HFETs. Characterization on epitaxial structure and HFET devices will be reported.

4:10 PM

CC3, Source-Drain Regrowth by MBE in Metal-Face AlN/GaN HEMTs: *Chuanxin Lian*[1]; Yu Cao[1]; Ronghua Wang[1]; Guowang Li[1]; Tom Zimmermann[1]; Debdeep Jena[1]; Huili Xing[1]; [1]University of Notre Dame

AlGaN/GaN HEMTs have established themselves in high speed high power electronic applications, thanks to the large breakdown field, heterostructure design freedom, and unique polarization-induced 2DEG properties. A challenge in improving the HEMT frequency performance is scaling down the device dimension both laterally and vertically at the same time without sacrificing the 2DEG transport properties. Compared with AlGaN/GaN, AlN/GaN structures allow very small gate-2DEG distance (1-4 nm) for the ease of vertical scaling while maintaining decent 2DEG properties: large 2DEG density, high mobility and good charge confinement . Besides downscaling of the device dimension, low source/drain contact resistance is also required for high frequency performance. By far, the ohmic contact resistance on AlN/GaN source/drain areas is usually above 0.4 ·mm due to the large energy barrier height of AlN. In this work, we have explored the source/drain regrowth with heavily-doped (In)GaN materials on metal-face AlN/GaN heterostructures. The AlN/GaN heterostructure sample used in this work was grown by MBE in a Veeco Gen 930 system. The AlN barrier is 4 nm thick; and the 2DEG density and mobility are measured to be 3.1e13 cm-2 and 1193 cm2/V.s, resulting in a sheet resistance of 170 /sq. Other GaN HEMT structures have also been used for developing the device fabrication and regrowth processes. The HEMT source/drain areas were first etched, and then, using tungsten as regrowth mask, heavily doped (Si: ~ 10e20 cm-3) InN(30 nm)/graded-InGaN(50 nm)/GaN (20 nm) were regrown by MBE. Control samples were also prepared by regrowing the same structure on semi-insulating GaN templates for further characterization. After regrowth, the amorphous material deposited on the tungsten mask was removed by molten KOH, and the tungsten mask was removed by H2O2. The XRD scans on the control samples reveal that a linearly graded InGaN from GaN to InN can be successfully regrown. The TLM measurement of non-alloyed Ti-based ohmic contacts deposited on a control sample indicates that contact resistances of ~ 0.2 ·mm with sheet resistances of ~ 100 /sq can be achieved on the regrown InN/InGaN/GaN. In the first regrowth experiment of source/drain on a HEMT, a gap was observed between the regrown material and the 2DEG channel, leading to a large contact resistance. To eliminate the gap, the migration enhanced epitaxy (MEE) technique was applied. After exploring several growth conditions, no gap was seen under SEM and AFM imaging. However, electrical measurements using non-alloyed Ti-based contacts on the regrown source/drain in HEMTs showed unacceptably large resistances. To understand its causes, the transmission electron microscope investigation is under way to interrogate the regrowth-sidewall interface. Studies are also currently being carried out to minimize damages to the 2DEG channel during the sample preparation as well as regrowth.

4:30 PM Student

CC4, AlGaN/GaN High Electron Mobility Transistors for Large Current Operation Achieved by Selective-Area Growth Using Plasma-Assisted Molecular Beam Epitaxy: *Liang Pang*[1]; Hui-Chan Seo[1]; Patrick Chapman[1]; Philip Krein[1]; Jung-Hee Lee[2]; Kyekyoon Kim[1]; [1]University of Illinois at Urbana-Champaign; [2]Kyungpook National University

GaN is a promising candidate material for high-power device applications. Although much progress has been made on GaN-based microwave power devices, power switching devices are still a new and immature research area, despite the fact that they have wide applications like inverters. In developing devices for power-switching applications, there are three key challenges: achievement of low on-state resistance, high current density and high breakdown voltage. We previously reported that selective-area growth (SAG) by plasma-assisted molecular beam epitaxy (PAMBE) is able to improve the contact resistance and current density over conventional contact scheme including ion-implantation. Twofold increase in the breakdown voltage also shows that unlike ion-implantation, SAG does no harm to the device breakdown behavior. In this study, SAG is employed to fabricate high electron mobility transistors (HEMTs) for high current operations. Furthermore, use of a gate insulator is investigated to confirm that GaN HEMTs processed by SAG is able to achieve

high breakdown voltages. An $Al_{0.26}Ga_{0.74}N$ (25 nm)/GaN (50nm)/semi-insulating GaN (2.2µm) on sapphire substrate prepared by MOCVD was used as the starting material. Device isolation and recessed drain/source structure were achieved by dry etching. SAG was done by growing a 54nm thick n^+-GaN layer ($1.0x10^{19}cm^{-3}$) with PAMBE and subsequently removing the poly-GaN and SiO_2 mask by a molten KOH solution. Alloyed metals of Ti/Al/Ti/Au were deposited on n^+-GaN for the Ohmic contact, and Ni/Au metals for the Schottky gate. For gate insulation, a layer of SiN/SiO_2 was deposited by PECVD in the gate region before gate metal deposition. Each device unit consisted of four HEMTs (W_g=100µm) sharing the same source, drain and gate electrodes. 15 device units were connected by wire bonding for large current operations. Single device unit processed via SAG showed a current of over 0.1A, more than twice that of the one without SAG. Significant improvement of on-state resistance was also observed. A maximum current of 1.4A was achieved for a total gate width of only 6mm. The current density was higher than many of the previously reported values, demonstrating that same current level can be achieved with smaller device area when SAG is employed. Schottky property between the gate and the drain for single device unit was studied. At V_{gd}=200V, the gate leakage was as low as 0.7mA. The breakdown voltage under high current operation will be measured by the curve tracer, and the power device figure of merit (FOM) will be investigated.

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CC5, Transport Studies of AlGaN/GaN Heterostructures with Variable SiN$_x$ Passivant Stress: Tamara Fehlberg[1]; Jason Milne[1]; Gilberto Umana-Membreno[1]; Stacia Keller[2]; Umesh Mishra[2]; Brett Nener[1]; *Giacinta Parish*[1]; [1]The University of Western Australia; [2]University of California (Santa Barbara)

It is well known that AlGaN/GaN-based transistors are highly suitable for high power and/or high frequency, robust operation in applications such as RF and mm-wave communications, power electronics and more. To achieve success in development of such devices it has been necessary to introduce steps to circumvent certain properties that are device-detrimental, some of which are not yet completely understood. One such issue is that of the use of dielectric layers. These have been introduced as passivation to combat the well-known issue of DC-RF current dispersion, for field plating, and for gate dielectrics to achieve enhancement-mode devices, necessary for power switching applications. For the most part, the effect of the introduced dielectric layers has been investigated with respect to overall transistor device performance, that is, macroscopic parameters such as drain current, rather than the effect on the 2DEG channel itself. However, assessing the changes induced in the transport properties of the 2DEG as a result of application of these layers is an important step in gaining a better understanding of the role of these layers in altering device performance. In this work, the influence of passivation with silicon nitride of different stress states on the 2DEG transport in $Al_xGa_{1-x}N$/GaN heterostructures is presented for the first time as a function of varying Al mole fraction (x). Samples from four heterostructures with x = 0.15, 0.23, 0.29 and 0.35 were deposited with SiN$_x$ by plasma enhanced chemical vapour deposition under compressive, neutral (slightly compressive), and tensile stress conditions (stress was measured for the same films deposited on silicon wafers). For each piece (different compositions and different SiN$_x$ layers) Hall bars were fabricated and the transport properties were measured using a variable magnetic field Hall technique, at 25, 77, 150 and 300K, up to 12T magnetic field. All types of SiN$_x$ passivant induced an increase in 2DEG concentration, consistent with previous published results for SiN$_x$ passivation. In addition, however, the 2DEG mobility increased significantly after passivation for the sample with x = 0.15. The more tensile the film stress, the greater was the percentage increase in mobility. However this percentage change decreased with increasing Al mole fraction. It is evident that silicon nitride passivation of $Al_xGa_{1-x}N$/GaN structures induces different changes in 2DEG carrier concentration and mobility, dependent on both stress in the SiN$_x$ thin film and the Al mole fraction. It is equally apparent that there is a complex relationship between these different factors, and that the stress in the SiNx passivation layer plays some, but not always the principal, role in determining the 2DEG transport properties. Thus tailoring of the deposition conditions to optimise transport properties is critical for a given passivant and Al mole fraction, to maximise device performance.