
Session Z:
Molecular Electronics:
Devices, Materials and Contacts

Friday AM Room: 126
June 22, 2007 Location: DeBartolo Hall

Session Chairs: Curt Richter, National Institute of Standards and Technology; David Janes, Purdue University

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8:20 AM Student

Z1, Ultra-High Vacuum Scanning Tunneling Microscopy Characterization of Nitroxyl Free Radicals on the Si(111)-7x7 Surface: *Qing Hua Wang*[1]; Nathan Guisinger[1]; Shaun Elder[1]; Nathan Yoder[1]; Mark Hersam[1]; [1]Northwestern University, Department of Materials Science and Engineering

In recent years, the molecular electronics community has shown substantial interest in molecule/semiconductor junctions. In particular, the study of organic molecules on silicon substrates holds promise for novel molecular electronic devices that can be directly interfaced with conventional microelectronic technology. The vast majority of previous work in this field has focused on organic molecules bound to Si(100)-2x1 or Si(111)-1x1 surfaces.[1] However, the tight spacing between reactive sites on these surfaces presents strict steric constraints that discourage ordered adlayers for all but the simplest organic molecules. The resulting non-uniformity of these organic adlayers has implied spatial variability in charge transport measurements.[2] On the other hand, the increased adatom dangling bond spacing on the Si(111)-7x7 surface relaxes these steric constraints for molecules that react via a single-site binding mechanism. Consequently, in this study, the ultra-high vacuum (UHV) scanning tunneling microscope (STM) is employed to study the structure and electronic properties of the nitroxyl free radical, 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO), on the Si(111)-7x7 surface.[3] TEMPO reacts with silicon dangling bonds via a single-site binding mechanism that results in a covalent Si-O bond. UHV STM investigation of the adsorption of TEMPO on the Si(111)-7x7 surface shows a preference toward binding to the center adatom dangling bond sites at low coverage. As coverage increases, the ratio of TEMPO molecules adsorbed to corner and center adatom sites approaches 1:1. Ultimately, at full saturation, the TEMPO adlayer is well-ordered and appears to preserve the underlying 7x7 reconstruction. The controlled structure of TEMPO on Si(111)-7x7 lends itself to further electrical characterization such as scanning tunneling spectroscopy (STS). Preliminary STS results suggest delocalized charge transfer between TEMPO molecules and the surrounding Si(111) surface. The implications of this charge transfer for molecular electronics and subsequent surface chemistry will be discussed. [1]N. P. Guisinger, N. L. Yoder, and M. C. Hersam, *Proc. Nat. Acad. Sci. USA*, 102, 8838 (2005). [2]N. P. Guisinger, R. Basu, M. E. Greene, A. S. Baluch, and M. C. Hersam, *Nanotechnology*, 15, S452 (2004). [3]N. P. Guisinger, S. P. Elder, N. L. Yoder, and M. C. Hersam, *Nanotechnology*, 18, 044011 (2007).

8:40 AM Student

Z2, Molecular Orbital and Dipole Effects in Metal-Molecule-Silicon Systems: *Adina Scott*[1]; Chad Risko[2]; Mark Ratner[2]; David Janes[1]; [1]Purdue University; [2]Northwestern University

Electrical transport through molecular layers on silicon is a topic of great interest for molecular electronics applications. Molecules can be robustly, covalently bound to silicon surfaces. Device properties can be tailored both by changing the surface chemistry and by modulating the electronic properties of the semiconductor through traditional doping techniques. In addition to these advantages, silicon is a technologically relevant material for electronics applications. Metal-molecule-silicon (MMS) devices were fabricated using traditional microfabrication techniques combined with this electrochemical grafting of *para*-substituted aryl-diazonium salts. Current-voltage (IV) and capacitance-voltage (CV) measurements have been performed. Density functional theory calculations were performed and the dipole moments and frontier molecular electronic orbital energies of the isolated molecules were determined. These calculated molecular properties can be correlated with observed electrostatic and transport properties of the devices. The electronic properties of MMS devices are dependent on both the molecular layer and semiconductor band effects. We interpret electronic transport by considering the semiconductor barrier and the transmission through the molecule separately. The semiconductor barrier is difference between the Si surface potential and the metal work function, ϕ_B. In an ideal metal-semiconductor structure, this quantity is simply the Schottky barrier. For MMS structures, ϕ_B is modulated by the dipole moment and dielectric nature of the molecular layer. This effect has been quantitatively studied by correlating barrier heights determined by CV measurements with the calculated molecular dipoles. The measured changes in ϕ_B correlate with the dipole moments of the isolated molecules but the overall effect is small, on the order of 15meV/Debye. IV characteristics have been qualitatively analyzed considering ϕ_B and the calculated molecular electronic levels. One feature of these aryl species that makes them particularly interesting for such studies is that the highest occupied molecular orbitals of the isolated molecules are close, and in some cases above the gold work function energy. It is found that when ϕ_B is large, there is no discernable modulation of current due to the molecular levels. When the energy bands line up and ϕ_B is small, either due to doping or by appropriate biasing, trends in current can be qualitatively correlated with the position of the nearest molecular electronic orbital. This suggests that under appropriate electrostatic conditions, transport occurs through a mechanism where the molecular electronic states play a key role in modulating current flow in the device.

9:00 AM Student

Z3, Atomic Resolution Assembly and Characterization of Organohalide Functionalized Silicon Surfaces: *Michael Walsh*[1]; Rajiv Basu[1]; C. Kinser[1]; J. D. Tovar[1]; Mark Hersam[1]; [1]Northwestern University

Molecular functionalization of silicon surfaces enables the fabrication of molecular electronic and sensing devices that are compatible with conventional microelectronics. Previous research in this field has established that many 1-alkenes will form dense adlayers on hydrogen passivated silicon surfaces under appropriate reaction conditions. For example, styrene molecules form one dimensional nanostructures on the Si(100)-2x1:H surface via a radical chain growth mechanism.[1] Styrene has also been shown to react with Si(111):1x1:H surfaces initiated by thermal and photochemical treatments.[2] While styrene is amenable to controlled adlayer formation, it lacks chemical functionality, thus limiting its utility for the fabrication of sophisticated molecular electronic and sensing devices. Consequently, in this study, the assembly and characterization of 4-bromostyrene on silicon surfaces is delineated.[3] The incorporation of bromine within organic adsorbates offers several advantages. Heavy atoms provide ideal X-ray fluorescence tags that may be used to interrogate the adsorbed molecules. Furthermore, using recent advances in Pd-mediated cross-coupling strategies,[4] organohalides also serve as useful synthetic handles through which more chemically elaborate structures may be built off of the surface. The structure and chemistry of 4-bromostyrene on Si(100)-2x1:H and Si(111)-1x1:H have been characterized with ultra-high vacuum (UHV) scanning tunneling microscopy (STM) and x-ray photoelectron spectroscopy (XPS). UHV STM experiments confirm that 4-bromostyrene forms one dimensional nanostructures from isolated dangling bonds on the Si(100)-2x1:H surface. Furthermore, XPS shows that the bromine moiety remains intact provided a moderate concentration of initial dangling bonds on the surface. However, as the dangling bond concentration increases to that of a UHV prepared clean silicon surface, the XPS spectra reveal evidence of Si-Br bonds suggesting a homolytic cleavage of the C-Br bond and a loss of the functionality of the molecular adlayer. Adlayers of 4-bromostyrene were also photochemically formed on UHV prepared Si(100)-2x1:H and wet chemically passivated Si(111)-1x1:H. The XPS spectra for these surfaces show that the bromine functionalization remains intact. The combination of UHV STM and XPS has revealed the conditions under which functional 4-bromostyrene adlayers and nanostructures can be prepared on hydrogen passivated silicon surfaces. The extension of this work to additional organohalides will also be discussed. [1]G. P. Lopinski, D. D. M. Waymer, and R. A. Wolkow, Nature 406, 48 (2000). [2]J. M. Buriak, Chem. Rev. 102, 1271 (2002). [3]R. Basu, C. R. Kinser, J. D. Tovar, and M. C. Hersam, Chem. Phys. 326, 144 (2006). [4]A. F. Littke, L. Schwarz, and G. C. Fu, J. Am. Chem. Soc. 124, 6343 (2002).

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Z4, Electronic Properties of Redox-Active Organic Molecules in Metal-Molecule-Metal Junctions: *Ajit Mahapatro*[1]; Jiewen Ying[1]; Kumar Parimal[2]; Amar Flood[2]; Tong Ren[1]; David Janes[1]; [1]Purdue University; [2]Indiana University

Molecular electronic concepts are of interest for possible memory or chemical sensing applications. Although studies involving non-resonant tunneling through molecules are informative, devices in which the molecular levels are close to the metal Fermi level allow resonant tunneling and could provide suitable structures for the proposed applications. Conduction studies of redox active molecules with suitable contacts can allow investigation of the energy- band alignments of the molecular levels with respect to the contacts, as well as studies of molecular in specific charge states. Electronic properties of organic molecules have been studied in metal-molecule-metal (MMM) junctions. A recently developed technique to efficiently fabricate stable nanogaps[1] of molecular scale lengths using room temperature electromigration breaking of gold (Au) micro-wires, provides a suitable device structure for single/few molecular systems, and allows room-temperature electrical measurements of various organic molecules within these nanogap molecular junctions (NMJs). Electronic properties of redox active molecules Oligo(phynilene ethylene), OPE and diruthenium-tetra(2-anilinopyridinate)[s-oligo(phenyleneethynyl)], $Ru_2(ap)_4(OPE_1)_2$ are studied in the NMJs. The OPE devices exhibit conductance (G) comparable to reported values at biases below 1.5V, and switching behavior at a threshold voltage between 1.6V and 3.0V. Current-voltage (I-V) characteristics through the $Ru_2(ap)_4(OPE_1)_2$ functionalized NMJs exhibit a peak at low bias (~0.3-0.4V) followed by a shoulder at higher bias (~1.0-1.2V). The G-V relationship shows a negative differential resistance behavior at lower bias followed by a conductance peak at higher bias. These features are prominent during the first voltage scan towards higher voltage both in +ve and –ve direction but are absent during return voltage sweep to V=0. Assuming equal capacitive coupling at both the metal-molecule contacts, the observed peak positions at ±0.25 ± 0.05V and ±1.05 ± 0.15V can be explained as molecular levels that are 0.13 and 0.6eV away from metal electrode (Au) Fermi level ($E_{f(Au)}$). These values along with the $E_{f(Au)}$ yield estimated values of E_{HOMO} = 5.23eV and E_{LUMO}=4.6 eV for the $Ru_2(ap)_4(OPE_1)_2$ molecule. This is in close agreement with the molecular level energies of E_{HOMO}=5.3eV, E_{LUMO}(1=4.22eV, as estimated from the measured oxidation (+0.67V) and reduction (-0.41V) peaks in the cyclic voltammogram with a Ag/AgCl reference electrode[2]. The small difference in the electrochemical and nanogap junction techniques may be due to the environment effect (counter ion effects in CV measurements). We have also investigated Bisthiolbiphenyl (BSBIPY) and find conductance peaks at ±1.0V. Comparable experiments on 4,4’-[1,4-phenylenebis(methyl dinitrilo)]bisbenzenethiol (PMNBT), but using a scanning probe tips as one contact, show peaks at ±1.6V. The observed peaks are believed to correlate to the relative positions of the levels in the respective molecules. References: [1]A. K. Mahapatro, S. Ghosh, D. B. Janes, *IEEE Trans. Nano Tech.*, 5, 232 (2006). [2]T. Ren *et. al., J. Organ. Chem.*, 690, 4734 (2005).

9:40 AM Student

Z5, Dramatic Resistance Increase and Magnetic Ordering with Molecular Spin-Valve Electrodes: Bruce Hinds[1]; *Pawan Tyagi*[1]; Stephen Holmes[1]; [1]University of Kentucky

Fabrication of devices based on the spin-state of magnetic molecules remains a difficult challenge due to the lack of a reliable molecular electrode fabrication process. We have fabricated magnetic molecular junctions (MMJ) by having paramagnetic molecular cluster molecules span across the surface (at the exposed pattern edge) of a metal-insulator-metal multilayer junction [Ta/Co/NiFe/Al_2O_3(~2nm)/NiFe]. The paramagnetic cyanide-bridged octametal complexes, $[(pzTp)Fe^{III}(CN)_3]_4\neg[Ni^{II}(L)]_4\neg[O_3SCF_3]_4$ [(pzTp) = tetra(pyrazol-1-yl)borate; L = 1-S(acetyl)tris(pyrazolyl)decane] is slightly larger (~2.5nm) than the thickness of the Al_2O_3 film layer, which is the critical dimension of this electrode geometry. The clusters were covalently-linked onto each ferromagnetic electrode, spanning the insulator layer and thus forming a dominant conduction pathway for the MMJ device. Interestingly the current dramatically decreased from ~1µA to ~1nA (RT, 100mV bias, 5x5µm cross junction area) a short time after molecular attachment, presumably due to magnetic ordering induced by the molecules acting as spin-valves. Magnetic force microscopy (MFM) showed strong antiferromagnetic coupling between the top and bottom magnetic electrodes. SQUID- magnetic susceptibility studies on an array of MMJ dots (4µm diameter) showed reduction in magnetization after molecular attachment, consistent with antiferromagnetic coupling and the dramatic changes in magneto-junction current (µA to pA). Low temperature and in-plane magnetization (77 K, 0.4T) further decreased the junction current to ~1pA level. Heating of the MMJ up to 400K established the higher current state temporarily (~1µA at 100mV measured at RT) by disrupting magnetic ordering. Cooling of the heated MMJ (at higher current state) to 77K again produced ~pA current range. Warming up of the cooled MJ up to 295K did not raise the current level above ~1nA. Dramatic current reduction effects MMJ were observed on >100 devices. A number of control experiments were also performed to verify the observations. Attachment of alkane molecules (without paramagnetic metal cluster) on the exposed edge of MMJ showed modest current increases without the dramatic drop in current. Attachment of magnetic molecules on the exposed edge of non magnetic tunnel junctions (Cu/AlOx(2nm)/Cu and Ta/AlOx(2nm)/Ta) also increased the tunnel junction current without exhibiting the dramatic decrease in current seen in magnetic junctions. The dramatic change in transport across the device is only possible with the combination of paramagnetic molecule and magnetic thin film electrodes, consistent with a molecular spin-valve induced magnetic ordering.

10:00 AM Student

Z6, Measurement of Tunneling Currents through Alkanes Assembled on Silicon with Aluminum Contacts: *Divesh Kapoor*[1]; Justin Jackson[1]; Feng Zhang[2]; Matthew Linford[2]; Mark Miller[1]; [1]University of Utah; [2]Brigham Young University

Most molecular contact devices developed to study electrical transport through self-assembled monolayers (SAMs) and single molecules have employed gold contact electrodes because of the convenience of gold-thiol chemistry and the resulting electronic structure. However, high-quality, covalently bonded SAMs on silicon may also be formed, and such a process could avoid the problems of introducing gold into a silicon-based integrated device technology. We report here on n-Si/SAM/Al structures within lithographically fabricated contact devices. Two molecules were used to form alkane SAMs in device structures, 1-dodecene ($C_{12}H_{24}$) and 1-hexadecene ($C_{16}H_{32}$). Pores of approximately 100 nm were opened in silicon nitride layers that covered lithographic n-type silicon electrodes, and the SAMs were formed on the exposed silicon. The monolayers on silicon were prepared from 1-alkenes and hydrogen terminated Si(100). Two of the biggest challenges in fabricating the devices were to make the process compatible with the chemistry involved in the formation of the molecular monolayer and to form a metal top contact with minimal defects. To avoid penetration of the aluminum through the molecular monolayer, we used indirect sputtering of aluminum. In this technique, the surface of interest was kept facing away from the aluminum target as opposed to the standard practice of keeping it in front of the target. This method lowered the number of shorts in our devices. Room temperature current-voltage measurements gave currents of similar magnitudes to those reported for Au/SAM/Au devices, and the current densities measured for the C_{16} devices were a factor of 10 smaller than for the C_{12} devices. Temperature dependent current-voltage measurements were performed to study the mechanism of electronic tunneling through alkane chains. The overall electrical yield was high, with the majority of fabricated devices exhibiting similar characteristics. In plotting conductivity versus voltage, we observe small peaks near zero bias. From our measurements we conclude that such n-Si/SAM/Al structures have suitable electronic structure for developing contact to molecules.

Session AA:
Oxide Thin Film Integration II

Friday AM June 22, 2007
Room: 129
Location: DeBartolo Hall

Session Chairs: Susanne Stemmer, University of California, Santa Barbara; Evgeni Gusev, Qualcomm

8:20 AM Student

AA1, Physical and Electrical Characterization of Nb-W, Ti-W and Pt-Ti Bilayer and Alloy Metal Gate Electrodes for Advanced CMOS Applications: *Gloria Wong*[1]; Ching-Huang Lu[1]; Michael Deal[1]; Yoshio Nishi[1]; Bruce Clemens[1]; [1]Stanford University

Metals are a promising candidate for the replacement of polycrystalline silicon as the gate electrode in CMOS devices as they eliminate both depletion effects in the polycrystalline silicon and boron penetration into the channel region. One of the most significant challenges remaining in the implementation of metal gates, however, is the issue of work function tuning. One method that has been proposed to tune the work function of the gate electrode is to use a bilayer metal gate. By using two metals with different work functions, the gate electrode work function can be tuned from that of one metal to the other. This is achieved by changing the thickness of the bottom metal layer. Ab initio simulations predict that the work function should be changed abruptly when 1-2 monolayers (~0.5nm) of the bottom layer metal is present. However, we have shown experimentally that a significantly thicker bottom metal layer is required to completely eliminate the influence of the top metal on the gate electrode work function. For Nb-W, at least 2.5nm of bottom layer metal is required, while for Pt-Ti, the minimum thickness is 6nm. Diffusion plays a critical role in determining the minimum layer thickness required. Nb-W is a refractory metal pair, and is thus expected to undergo minimal interdiffusion during typical process annealing conditions (400°C, 30min). On the other hand, greater diffusion is expected in the Pt-Ti system, and as a result, we observe a more gradual transition in work function over that of Nb-W. We model the diffusion, taking into account the ratio of densities of states at the Fermi level and predict the diffusivities of the metal-metal pairs. The effect of composition on the work function is directly probed by fabricating alloy samples of Nb-W, Ti-W and Pt-Ti using DC magnetron co-sputtering. It was found that the work function is non-linear with composition. From their respective equilibrium phase diagrams, these three systems exhibit dissimilar properties: Nb-W exhibits complete solid solubility, Ti-W exhibits a two-phase region, and several compounds are predicted to form in the Pt-Ti system. Thus, the structure and orientation of both alloy and bilayer electrodes is investigated using x-ray diffraction. We further probe the nature of the interface bonding using XPS. Given the need for thermal stability in these devices, we investigate the diffusion behavior by performing x-ray reflectivity measurements on multilayered films. We confirm that Nb-W exhibits the least diffusion out of the three systems studied, and estimate the amount of diffusion and interface mixing that occurs during annealing. The results indicate that diffusion of the top metal atoms is likely through the grain boundaries.

8:40 AM Student

AA2, Two-Step Annealing Silicidation Process in NiSi-Gated MOSFET: *Jun Liu*[1]; DimLee Kwong[1]; [1]University of Texas at Austin

Metal gate electrodes are projected to be introduced into future CMOS devices in order to achieve Equivalent Oxide Thickness (EOT) <1nm and avoid poly depletion effect according to ITRS Road Map (Year 2005). Metal gates have many advantages over poly-Si gate, such as no poly depletion effects, no boron penetration, low resistance and suppressed remote charge scattering. Recently, fully silicided metal gate (FUSI) appears increasingly attractive due to their simpler implementation in a conventional CMOS integration flow. Dopants such as arsenic and boron pile-up at the NiSi-SiO$_2$ interface was reported and suggested to be the cause for FUSI work function modification. However, commonly used one-step silicidation process (450°C~550°C 30s) in FUSI metal gate drives extra Ni from spacer and surrounding area into gate electrode, causing Ni/Si larger and the changes of Ni silicide phase, and then the work function of gate electrode could be instable. Two-step silicidation could avoid this problem. First step annealing (RTP1 usually 300°C~400°C) is a low-temperature process which drives little extra Ni into the gate. Before second step annealing (RTP2>, usually 500°C 30s), the extra Ni is etched off in the mixture of H_2SO_4, H_2O_2 and H_2O, and therefore, the Ni/Si ratio will be maintained. In this paper, two step silicidation process is used on the structure of Ni/poly Si (pre-implanted with dopants)/SiO$_2$/Si substrate, and dopant impacts on Ni-Si reaction rate, NiSi phase formation and work function tuning are extensively discussed. These following results are found: In the same RTP1 conditions, As-doped and B-doped samples are found to have different Ni-Si reaction rate. As is found to assist silicidation process and B has no effect on Ni-Si reaction rate. The dopant effect on Ni-Si reaction rate has impacts on FUSI conditions, NiSi phase formation, and work function tuning of NiSi FUSI metal gates. RTP1 temperature also is found to be important fact in deciding Ni phase composition and work function tuning. The ideal two-step silicidation conditions are also found for NMOS and PMOS NiSi gates.) In order to acquire lower threshold voltage for both N- and PMOS, for NMOS (As-doped) NiSi gate, 325°C 30sec/ 500°C 30sec is favorable to acquire a low NMOS work function while for PMOS (B-doped) NiSi gate, 400°C 30sec/ 500°C 30sec is needed to achieve FUSI.

9:00 AM Student

AA3, Electrical Characterization of Molecular Beam Deposited LaAlO$_3$-GaAs and Annealing Effects: *Donghun Choi*[1]; James Harris[1]; Maitri Warusawithana[2]; Darrell Schlom[2]; Niti Goel[3]; Wilman Tsai[3]; [1]Stanford University; [2]Pennsylvania State University; [3]Intel Corporation

The lack of useful surface passivation for compound semiconductor has precluded development of MOS devices and caused high surface recombination parasitics in scaled devices for the past 30 years. The development of high performance MOS devices demands new surface treatments techniques and materials to reduce the interface state density (D$_{it}$). Here, we investigate the use of molecular beam deposited (MBD) lanthanum aluminate (LaAlO$_3$), its annealing effects and characterize the interface using C-V, I-V and XPS measurements. A 300nm epi-GaAs layer was grown by MBE on p-type GaAs wafer. Prior to unloading the wafer, a thick amorphous arsenic cap layer was deposited at room temperature using an As$_2$ flux to protect the surface from oxidation and contamination during wafer transfer in air. Two different surface conditions were prepared in the MBD chamber by thermal Arsenic desorption. The surface was monitored by in situ reflection high-energy electron diffraction (RHEED) to control the surface reconstruction pattern: i) Arsenic-rich c(4x4) surface, ii) Arsenic-stabilized (2x4) surface. After the sample was cooled down to 80°C, an 8nm amorphous LaAlO$_3$ film was deposited. Aluminum (100 nm) dots were e-beam evaporated on the samples. Two kinds of anneals were performed to improve the dielectric and interface qualities: Forming Gas Anneal (FGA), Rapid Thermal Anneal (RTA). The MOS capacitors were characterized by C-V and I-V measurement. The C-V characteristics of as-deposited c(4x4) showed stretched-out curves at high frequencies and significant frequency dispersion. However, relatively small bidirectional C-V hysteresis was observed. FGA was performed at a low temperature (~ 300°C) to avoid Arsenic diffusion for 80 minutes. This FGA significantly reduced frequency dispersion (100~150mV) while still maintaining the small hysteresis (50 mV). In contrast, the RTA degraded the C-V hystersis and frequency dispersion. The C-V curves of the as-deposited (2x4) samples were distorted by donor-like interface states with frequency dispersion and C-V hysteresis. Unlike the c(4x4) samples, the FGA failed to significantly improve C-V characteristics. However, a post metal deposition RTA (PM RTA) efficiently solved these issues; C-V hysteresis : ~50mV, frequency dispersion : ~50mV, results comparable with the Ga$_2$O$_3$-GaAs results reported by M.Passlack et al. XPS depth profiles revealed no As$_2$O$_3$ or Ga$_2$O$_3$ either at the interface or in the LaAlO$_3$ layer and no chemical shift of As 3d and Ga 3d peaks. The low leakage current density of $1x10^{-8}$ ~ $1x10^{-7}$ was measured at the flat band condition on both samples. Consequently, different optimized annealing conditions were achieved for (2x4) and c(4x4) sample. The best interface was produced by PM RTA (2x4) samples with low Dit and excellent electrical properties.

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AA4, MBE Growth of Ga_2O_3 and $(InGa)_2O_3$ Films with Ultraviolet Optical Functions: Takahito Oshima[1]; Tetsuya Okuno[1]; *Shizuo Fujita*[1]; [1]Kyoto University

In order to explore the deep ultraviolet optical functions with a new material, we have paid attention to Ga_2O_3 and $(InGa)_2O_3$ thin films and their heterostructures. Due to the wide bandgap of Ga_2O_3 (reported as 4.7-5 eV), optical functions in the deep ultraviolet region are readily achieved without alloying like AlGaN or ZnMgO, which sometimes causes problems of defect formation or phase separation. Here the attempts for MBE growth and characterization of these materials are reported. In the MBE system, Ga and In were supplied with Knudsen cells, and O_2 gas was supplied through an RF (13.56 MHz) plasma cell. In the growth of Ga_2O_3 on sapphire substrates, β-Ga_2O_3 was formed at 900°C with the epitaxial relationship β-Ga_2O_3(-201)// sapphire (0001), but the β-Ga_2O_3 possessed in-plane rotational domains of 120 and 240-degrees. Further, the inclusion of α-Ga_2O_3 was not completely be eliminated. In spite of the remaining problems, the layer was completely transparent in the visible region and the bandgap energy was found to be 5 eV by optical transmission measurements. The cathodoluminescence (CL) at room temperature exhibited the near band edge emission around 265 nm though the total spectrum was dominated by deeper emissions peaking at 360-370 nm. The bandgap energy was lowered with $(In_xGa_{1-x})_2O_3$ films from 5 eV (x=0) to 4.6 eV (x=0.13). The x-ray photoemission spectroscopy (XPS) revealed the type-I band discontinuity between Ga_2O_3 and In_2O_3, and therefore we can expect the carrier confinement double heterostructure or quantum well structure with the $(InGa)_2O_3/Ga_2O_3$ system. The metal-semiconductor-metal photodetector with a Ga_2O_3 film on sapphire exhibited the photoresponse only at the wavelength shorter than 300 nm, peaking at 240 nm. An advantage of Ga_2O_3 over GaN or ZnO is the easier availability of Ga_2O_3 substrates. The homoepitaxial growth resulted in complete streaky RHEED pattern upto at least 400 nm in thickness of the Ga_2O_3 layer and the step-terrace structure on the surface revealed by AFM. Further the homoepitaxial layer was single crystalline β-Ga_2O_3 without rotation domains observed on sapphire substrates. These results clearly support the potential of homoepitaxy, which will be reported in detail at the presentation.

9:40 AM Student

AA5, Molecular Beam Epitaxy of $YMnO_3$ on c-Plane GaN: *Cameron Keenan*[1]; Sandeep Chandril[1]; Esteban Ramos[2]; Guerau Cabrera[1]; A. Cabrera[2]; David Lederman[1]; Thomas Myers[1]; [1]West Virginia University; [2]Pontificia Universidad Católica de Chile

Among the ferroelectric oxides, $YMnO_3$ is a suitable candidate for ferroelectric/GaN heterostructures. GaN is a polar semiconductor, due to the lack of inversion symmetry in its structure and as a result is expected to produce a significant interaction with ferroelectric films. Both $YMnO_3$ and GaN have stable hexagonal structures and the in-plane lattice parameter of $YMnO_3$ (a = 6.139 to 6.148 Å) and roughly twice the lattice parameter of GaN (a = 3.189 Å) have only a 4% lattice mismatch assuming that the in-plane crystallographic directions are the same for both materials. GaN/$YMnO_3$ heterostructures were produced by molecular beam epitaxy (MBE) on (0001) GaN-on-sapphire templates prepared by hydride vapor phase epitaxy (HVPE). The surface structure was analyzed in-situ using reflection high energy electron diffraction (RHEED) and ex-situ using atomic force microscopy (AFM). X-ray diffraction and RHEED data suggest that the films grew with a (0001) orientation with an in-plane $YMnO_3$/GaN relationship of (0001)||(0001); [1-100]||[11-20]. This corresponds to a 30° rotation of the $YMnO_3$ film with respect to the GaN structure, and thus the lattice mismatch is greater than anticipated presumably as a result of an oxide layer formed at the GaN/$YMnO_3$ interface. The $YMnO_3$ was ferroelectric at room temperature with a remnant polarization of ~3.2 $\mu C/cm^2$ and a saturation polarization of ~12 $\mu C/cm^2$. Several samples prepared displayed localized, prismatic nanoscale structures that appear to consist of $YMnO_3$. The underlying origins of the formation of these structures is not clear, but there seems to be a correlation with the substrate temperature used to grow the layers. The volume of these structures is consistent with capturing the majority of the Y and Mn flux, and indicates a significant surface mobility for these atoms during growth. As $YMnO_3$ is ferroelectric, these nanostructures, and could serve to localize charge in the underlying GaN and the reversal of their polarization could be enhanced by the lack of lateral structural constraints. Current work is being done to characterize these structures using piezoelectric force microscopy. Ongoing efforts in this project are centered around producing better stoichiometry control using two in situ techniques, RHEED-total reflection x-ray spectroscopy (-TRAXS) and shuttered RHEED oscillations of the specular intensity [9]. RHEED-TRAXS is a method of using the x-rays induced by RHEED electrons to characterize the surface composition of a sample. We have shown monolayer sensitivity for both yttrium and manganese. This technique and shuttered RHEED oscillations are expected to allow much improved stoichiometry. This work was funded by the Office of Naval Research (Grant N00014-02-1-0974), the Air Force Office of Scientific Research (MURI grant F49620-03-1-0330), and the National Science Foundation (CIAM-DMR grant 0502825).

10:00 AM Break

10:20 AM

AA6, Structure and Ion Conduction Phenomena in Oxide Thin Films and Nanostructures: Masaru Tsuchiya[1]; Annamalai Karthikeyan[1]; Nana Ayensu[1]; *Shriram Ramanathan*[1]; [1]Harvard University

Thin film membranes of fluorite oxides such as yttria-stabilized zirconia are being actively investigated as solid electrolytes for potential applications in solid oxide fuel cells. Vapour deposition techniques being non-equilibrium processes may lead to altered defect chemistry in such nanoscale systems and subsequently quite different ion transport properties than bulk. Initial observations by some research groups indeed see unusual phenomena such as size dependence on ion conductivity. Tremendous research opportunities exist in understanding structure-stoichiometry-electrical property relationships in nanoscale oxide ion conductors. We report our on-going investigation into ion transport phenomena in thin film oxides such as yttria-doped zirconia (YDZ) and ceria conducted as a function of temperature and oxygen partial pressure. Detailed electrochemical impedance spectroscopy studies have been performed on thin film oxides synthesized by vapor deposition techniques such as sputtering and electron beam evaporation. Microstructure studies have been performed using both in-situ heating in a transmission electron microscope (TEM) as well as annealing in controlled ambient followed by electron diffraction and imaging analysis. We find that ion conductivity is size dependent and increases as film thickness decreases. An order of magnitude increase in conductivity is seen for 17nm thick polycrystalline YDZ films compared to bulk while activation energies for ion migration are similar across length scales. Further, modulus spectroscopy analyses have been performed to analyze the dielectric relaxation profiles for nanoscale oxides and compared to bulk single crystal data. Electrochemical measurements have been performed in various ambient ranging from air down to oxygen partial pressure of 10^-20 Torr to understand size effects on conduction mechanisms and defect chemistry changes at nanoscale. Detailed TEM studies show fascinating structural evolution as a function of thickness. It is seen that as-grown ~ 32nm thick YDZ films grown by e-beam evaporation are amorphous and crystallize near 500°C to form cubic phase while ~75nm thick films are polycrystalline as-grown. Structural transformations during high temperature processing show that metastable phases form upon annealing but rapidly evolve into cubic phase in YDZ system. Systematic comparison with pure zirconia films shows dramatic differences in phase formation. Understanding the structural aspects in nanoscale oxide systems is important in interpreting the electrochemical properties.

10:40 AM Student

AA7, Growth of Either (001) or (111) Epitaxial CeO_2 on R-Cut Sapphire by Modifying Conditions and an Analysis of the In-Plane Domain Matching Epitaxy Operative for Both Orientations: *Madhana Sunder*[1]; Peter Moran[1]; [1]Michigan Technological University

Epitaxial CeO_2 is an important intermediary buffer layer for subsequent integration of single-crystal (cubic) perovskite films on commercially available large-area Al_2O_3 (hexagonal) substrates. We have studied how film growth rate, substrate temperature, pre-growth substrate annealing, and post-growth heterostructure annealing impacts CeO_2 epitaxy on R-plane Al_2O_3. We report how these variables can be modified to grow either epitaxial single crystal (001) CeO_2 films, (111) CeO_2 films or films of mixed (001)/(111) orientation on the pseudocubic R-plane Al_2O_3 surface. CeO_2 thin films were grown on R-plane Al_2O_3 substrates using RF magnetron sputtering. Substrates were held at one of two temperatures during growth: 800ºC or 900ºC. Films were grown at one of 7 growth rates ranging between 0.04 nm/min to 0.86 nm/min, both on "as-received" substrates and substrates pre-annealed at 900mTorr O_2 for 3 hours at 900°C. The orientation, crystalline quality, and surface roughness of the films were characterized by high resolution x-ray diffraction and x-ray reflectivity both before and after a subsequent 3 hour 1023°C anneal in flowing O_2. CeO_2 grows on R-plane Al_2O_3 sapphire in either an (001) or (111) orientation. In general, low growth rates, higher substrate temperatures, and substrate pre-annealing lead to a higher volume fraction of (001) CeO_2. Films grown at 900°C using growth rates <0.11nm/min are 100% (001). Films grown at rates >0.76nm/min are 95% by volume (111)-oriented. Post growth annealing reduces surface roughness for all films. Mixed orientation films with at least a 53% volume fraction of (001) become entirely (001) oriented after the anneal, whereas films with <10% (001) CeO_2 become entirely (111)-oriented after a post-growth anneal. An examination of the in-plane epitaxial relationships for both (001) and (111) CeO_2 films demonstrate that in both cases domain-matching epitaxy is operative along the [110] CeO_2 and Al_2O_3 [0-2-21] directions. The data demonstrate that (001) CeO_2 films grew on the pseudocubic Al_2O_3 surface as a single domain with the CeO_2 [110] direction aligned to the Al_2O_3 [0-2-21] and the CeO_2 [1-10] to the Al_2O_3 [2-201]. In contrast, the data demonstrated that (111) CeO_2 films grew as 2 epitaxial domains rotated by 94.27° about the surface normal. The first domain grew with the CeO_2 [1-10] direction aligned to the Al_2O_3 [0-2-21] and the CeO_2 [11-2] to the Al_2O_3 [2-201]. The second domain grew with the CeO_2 [-110] along Al_2O_3 [2-201] and the CeO_2 [11-2] along Al_2O_3 [0-2-21]. These results are interpreted as being due to the presence in (111) CeO_2 films of an exceptionally low mismatch between 3 domains along CeO_2 [11-2] (14.07Å) and 4 domains along Al_2O_3 [0-2-21] (14.08Å).

11:00 AM Student

AA8, High-Resolution Synchrotron X-Ray Studies of Multiferroic $BiFeO_3$ Thin Films: *Jeffrey Klug*[1]; Orlando Auciello[2]; Michael Bedzyk[1]; Ying-Hao Chu[3]; Ramamoorthy Ramesh[3]; [1]Northwestern University; [2]Argonne National Laboratory; [3]University of California, Berkeley

The science and technology of Pb-free ferroelectric thin films is gaining more attention as the microelectronic industry is on schedule to phase Pb out of future micro- and nanoelectronic devices, including non-volatile ferroelectric random access memories (FeRAMs). This action will be due mainly to environmental concerns related the most extensively used ferroelectric material including Pb ($Pb(Zr,Ti)O_3$). In this respect, we report here on in situ synchrotron X-ray standing waves (XSW) and high-resolution X-ray scattering (crystal truncation rod (CTR) and grazing incidence X-ray diffraction (GIXD)) studies of magnetoelectric multiferroic $BiFeO_3$, which may provide the basis for creating environmentally benign piezoelectric-based sensors and actuators, and ferroelectric random-access memories (FeRAMs). Recent reports have shown that multiferroic $BiFeO_3$ thin films exhibit large room-temperature spontaneous polarization as well as a strong piezoelectric response. The data reported in the literature, along with coupled electric, magnetic, and elastic order parameters make $BiFeO_3$ an important material not only for possible piezo-/ferroelectric applications, but also for a new generation of multifunctional devices. We have applied the thin film XSW, CTR and GIXD techniques to study the strain and interface structure of $BiFeO_3$ (001) films grown on $SrRuO_3$ (001) coated $DyScO_3$ (110) and $BiFeO_3$ (111) films grown on $SrTiO_3$ (111) with atomic-scale resolution. With XSW, we measure the cation positions along the c-axis of the unit cell, which is a direct measurement of the effect of strain on domain polarity. CTR measurements have been used to quantify the interface structure and film morphology, and we have used GIXD to measure the in-plane film-electrode-substrate registry of $BiFeO_3$/ $SrRuO_3$/ $DyScO_3$ and $BiFeO_3$/ $SrRuO_3$/ $SrTiO_3$ samples. We will discuss the implications of the synchrotron X-ray data presented here on the ferroelectric performance of thin film $BiFeO_3$. This work was supported by the US Department of Energy, BES-Materials Sciences, under Contract DE-AC02-06CH11357.

11:20 AM

AA9, Epitaxial Growth of Rock Salt Oxides on Perovskite Substrates: Matthew Snyder[1]; Jian Xu[1]; Patrick Fisher[2]; Marek Skowronski[2]; Paul Salvador[2]; Oleg Maksimov[3]; *Volker Heydemann*[3]; [1]Pennsylvania State University, Department of Engineering Science and Mechanics; [2]Carnegie Mellon University, Department of Materials Science and Engineering; [3]Pennsylvania State University, Electro-Optics Center

In the recent years, an increasing technological and scientific interest in the epitaxial growth of oxides on semiconductors has evolved. Frequently, thin interfacial layers are required to achieve epitaxial growth of oxides with sufficient structural perfection and device performance on semiconductor substrates. Rock salt oxides are excellent candidates to serve as the interfacial layer between semiconductors and functional oxides. These oxides can be closely lattice-matched to semiconductors such as Si ($Ba_{0.72}Sr_{0.28}O$), GaN ($Mg_{0.5}Ca_{0.5}O$), and SiC ($Mg_{0.75}Ca_{0.25}O$), they can be deposited under low oxygen flux, and they form thermodynamically stable interfaces with semiconductors. Although heteroepitaxial films of rock salt oxides have been grown over the past two decades, no detailed studies of growth mode, structural properties, and crystalline quality of such films are found in literature. For example, while MgO films deposited on $LaAlO_3$ are rotated by 45°, no rotation is observed in MgO/$SrTiO_3$ system. Simple mismatch arguments predict that the unrotated epitaxy mode should be favored for all MgO films, as the 45° in-plane rotation increases lattice mismatch on both $LaAlO_3$ and $SrTiO_3$ substrates. Further research will be necessary to fully understand the factors determining the growth mode and epitaxial orientation of rock salt materials deposited on perovskites. Molecular beam epitaxy was used to study the effect of film/substrate lattice mismatch f on the growth mode and crystalline quality of the films. Films of SrO and MgO were grown on $LaAlO_3$, LSAT, $SrTiO_3$, and YSZ (100) substrates. The lattice mismatch in these systems varies from 4% (SrO/$LaAlO_3$) to 28% (MgO/YSZ). For low mismatch ($f < 8\%$), films such as SrO/$LaAlO_3$, SrO/$SrTiO_3$, MgO/$SrTiO_3$, or MgO/LSAT grow epitaxially in Stranski-Krastanov mode. As growth proceeds, the surface order improves and the islands coalesce resulting in a flat, terraced surface. SrO grows on $LaAlO_3$ and $SrTiO_3$ with a 45° in-plane rotation that reduces mismatch and aligns structurally similar directions. MgO grows unrotated on $SrTiO_3$ and LSAT, in agreement with mismatch arguments. For increased lattice mismatch ($f > 10\%$), growth of either polycrystalline (MgO/$LaAlO_3$) or heavily twinned (MgO/YSZ) films is observed. However, epitaxial growth can be promoted through the use of a relaxed buffer layer (MgO/$SrTiO_3$/$LaAlO_3$ or MgO/SrO/$LaAlO_3$). This work was supported by the Office of Naval Research under grant N00014-06-1-1018. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Office of Naval Research.

11:40 AM

AA10, RF Plasma MBE Growth and Characterization of $BiFeO_3$ and Bi_2FeCrO_6 Multiferroic Thin Films: Jiri Kabelac[1]; *Siddhartha Ghosh*[1]; P. Dobal[2]; Ram Katiyar[2]; [1]University of Illinois at Chicago; [2]University of Puerto Rico

Materials in which ferromagnetism and ferroelectricity occur simultaneously in the same phase and allow coupling between the ferromagnetic and ferroelectric phase are known as Magnetoelectric (ME) Multiferroics. In the area of single-phase thin films, most of the attention recently has been devoted to the oxides $BiFeO_3$, $BiMnO_3$, and $YMnO_3$. Interest in perovskite $BiFe_{O3}$ derives from the high electric and magnetic ordering temperatures of the bulk compound and the possibility of intrinsic multiferroic coupling. To manipulate the interactions in $BiFeO_3$, a broad range of chemical substitution schemes designed to enhance the ferroelectric (FE) coupling are utilized, induce magnetorestrictive (MR) behavior, and couple the two effects by creating multilayer composites. We propose to use MBE grown high quality $BiFeO_3$ (single perovskite) and Bi_2FeCrO_6 (double perovskite) as the primary material host. Epitaxy of modulated thin films provide additional opportunities for balancing the competing effects and enhance material response. The $BiFeO_3$ based thin films are grown, by oxygen plasma assisted MBE, on oxide and semiconductor substrates. RHEED is used to monitor surface quality and the stoichiometry of the $BiFeO_3$ and Bi_2FeCrO_6 films is measured using Rutherford Backscattering (RBS). Composition control to within fraction of a percent is achievable by measuring extremely slow growth rates using a retractable quartz crystal monitor. X-ray diffraction measurements show epitaxial $BiFeO_3$ (BFO) films with FWHM comparable to films grown by PLD. Polarized raman spectroscopy results show extremely crystalline films on STO (001) substrates. Preliminary measurements on the thin films show ferroelectricity but very weak magnetism at low temperatures. Films on Nb:STO have leakage currents ~ 0.1μA/cm^2 and remnant polarization ~ 28μC/cm^2. Films on $SrRuO_3$-STO have leakage currents ~ 8nA/cm^2 and remnant polarization ~ 56μC/cm^2. Nb diffusion and poor surface quality of Nb:STO can be attributed to the difference in ferroelectric and leakage properties of the BFO thin films grown on Nb:STO and $SrRuO_3$-STO. Bi based double perovskite magnetoelectric multiferroics such as Bi_2FeCrO_6 are being grown on STO (111) and investigated for enhanced magnetoelectric coupling in single phase materials as suggested recently by Spaldin et. al.[1] Field assisted raman spectroscopy and electrical and magnetic properties of both Bi based single and double perovskite thin films on STO will be discussed in detail.The single and double perovskite Bi based multiferroic thin films will provide an excellent platform for developing multiferroic thin film heterostructures on semiconductor substrates. Work is underway to establish heteroepitaxy of Bi based multiferroic perovskite thin films on GaN substrates for advanced tunable microwave devices on GaN. This work is being funded by Office of Naval Research (ONR) and NSF-NIRT program. [1]Pio Baettig and Nicola Spaldin, Appl. Phys. Lett. 86, 012505 (2005).

Session BB:
III-Nitride Processing and Characterization

Friday AM
June 22, 2007

Room: 102
Location: DeBartolo Hall

Session Chairs: Jung Han, Yale University; Thomas Myers, West Virginia University

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8:20 AM

BB1, Novel Concepts for AlGaN/MgZnO Hetero-Interfaces and Devices: *Andrei Osinsky*[1]; Brian Hertog[1]; A. Dabiran[1]; J. Xie[1]; P. Chow[1]; O. Lopatiuk-Tirpak[2]; L. Chernyak[2]; J. Mares[2]; A. Thompson[2]; W. Schoenfeld[2]; [1]SVT Associates, Inc.; [2]University of Central Florida

Recent progress in the development of ZnO-based materials demonstrates their potential for many important light emitting and thin film electronic applications.[1] In this presentation, we discuss the new opportunities that bang gap engineering offers in Type-II polarization field enhanced ZnMgO/GaN heterointerfaces for improved nitride device performances. Detailed modeling of the energy band diagrams of type-II n-MgZnO/p-AlGaN and n-MgZnO/n-AlGaN based heterostructures incorporating piezoelectric and spontaneous polarization has been performed.[2] In the simulations we assumed a relaxed/partially strained/strained type-II heterostucture with a 1 eV discontinuity in the VB. The AlGaN and MgZnO surfaces were also assumed to have Ga- and Zn-polarity, respectively. The hole accumulation layer formed at a strained interface can have a hole sheet density as large as 1.7×10^{13} cm^{-2}. Under forward bias, p-AlGaN/n-ZnO heterostructures form a 0.8eV deep triangular QW for electrons. The bias induced QW captures the electrons from the n-ZnO region enabling optical transitions at the interface. Type-II strained n-ZnO/n-AlGaN structures exhibit band bending resulting in a more than 3eV deep QW for hole confinement near the heterojunction interface. This QW can potentially accumulate non-equilibrium carriers with a very long lifetime. Electron beam induced current (EBIC) measurements have been performed on GaN/ZnO structures for determination of minority carrier diffusion length. The measurement results show a thirty times increase over what is observed in typical n-type GaN or ZnO films. The lateral diffusion length for non-equilibrium holes in n-type material was > 30 microns, which is unusually large for direct band gap materials. To confirm that the giant diffusion length is attributable to the interface EBIC measurements were performed at different accelerating voltages and temperatures. Lateral Schottky type MSM photodiodes were fabricated from n-ZnO/n-GaN structures. Spectral response characterization is presented for Schottky MSM photodiodes with different finger spacing to support the proposed minority carrier transport model. We will discuss the conceptual use of Type-II strained n-ZnO/n-AlGaN structures to enhance the performance of GaN LEDs. This work was partially supported U.S. Army Research Office under a program monitored by Michael Gerhold. [1]D. P. Norton, Y. W. Heo, M. P. Ivill, K. Ip, S. J. Pearton, M. F. Chisholm, and T. Steiner, Mater. Today 7, 34 (2004). [2]A. Osinsky, J. W. Dong, M. Z. Kauser, B. Hertog, A. M. Dabiran, P. P.Chow, S. J. Pearton, O. Lopatiuk, and L. Chernyak, Appl. Phys. Lett. 85, 4272 (2004).

8:40 AM

BB2, Inhomogeneous Nucleation of III-Nitride Films on 4H-SiC Mesa Substrates: *Yoosuf Picard*[1]; Mark Twigg[1]; Nabil Bassim[1]; Michael Mastro[1]; Charles Eddy[1]; Thomas Zega[1]; Richard Henry[1]; Jim Culbertson[1]; Ronald Holm[1]; Philip Neudeck[2]; Andrew Trunek[3]; J. Powell[4]; [1]Naval Research Laboratory; [2]NASA Glenn Research Center; [3]OAI; [4]Sest, Inc.

It is well established that optimal MOCVD GaN growth requires deposition conditions that minimize the GaN nucleation on the heteroepitaxial surface. Implicit in the development of MOCVD growth conditions is the assumption that the surface morphology of the substrate or nucleation layer does not greatly vary. In the case of nearly step-free 4H-SiC mesa substrates, however, such an assumption is seen to require considerable revision. Transmission electron microscopy, of MOCVD III-nitride films grown on 4H-SiC mesa substrates, reveals that the nucleation and growth of GaN films is strongly dependent on the morphology presented by the substrate surface. The presence of a screw dislocation penetrating the mesa substrate produces a stepped surface, thereby enhancing the nucleation and growth of the GaN film. On such a substrate the GaN film is seen to grow from the center of the mesa where the threading screw dislocation is situated, but with the result that the film does not always spread to the edge of the mesa. As for growth on a neighboring step-free mesa, it is observed that the GaN film does not nucleate due to the absence of threading screw dislocations. Although the growth of the GaN film is strongly dependent on the morphology of the nucleating surface, the AlN nucleation layer is seen to deposit even on step-free mesas where subsequent GaN growth is insignificant. However, the nature of threading dislocations within the AlN nucleation layer is strongly dependent on whether the mesa surface is stepped or unstepped. Specifically, AlN layers show a pronounced increase in lateral dislocations when grown on step-free mesas. These observations detail many issues important for utilizing templated 4H-SiC mesa substrates for high-quality III-nitride films. The spatial size (50-200 microns) of these mesas will determine the likelihood of screw dislocations penetrating the 4H-SiC substrate and producing a stepped surface. This in turn will influence the nucleation, coverage, types of defects, and dislocation densities of MOCVD III-nitride films.

9:00 AM

BB3, GaN Doped with Neodymium by Plasma-Assisted Molecular Beam Epitaxy: *Eric Readinger*[1]; Grace Chern[1]; Michael Wraback[1]; [1]U.S. Army Research Laboratory

Solid state laser applications using crystals doped with Nd have been quite successful and/or very promising (e.g., Nd:YAG). What these crystals lack is the ability to dissipate thermal energy, with thermal conductivities on the order of 5-15 W/m-K, which limits their high power operation. By changing the matrix to a wide bandgap semiconductor such as GaN (or AlGaN), with a thermal conductivity of 100-300 W/m-K, the improvement in heat extraction could allow for major gains in solid state laser technology. It has been shown previously that rare-earth (RE) dopants such as Er, Pr, Tm, and Eu are well-suited to III-nitride semiconductors [1-4]. Although there have been difficulties in preserving optical quality while achieving adequate concentrations, light emission from RE-doped GaN has been demonstrated by photoluminescence (PL), electroluminescence (EL), and cathodoluminescence (CL). Two techniques exist for the introduction of RE-dopants into the semiconductor matrix: ion implantation and in situ doping during growth. Ion implantation imparts damage to the matrix that can not be removed by annealing, and it creates a doping profile due to the depth limitations for implanting RE species. Kim and Holloway report the EL properties of GaN doped with Nd by in situ reactive sputtering [5]. We provide the first report for in situ doping of GaN with the RE element Nd by plasma assisted-molecular beam epitaxy (PA-MBE). GaN epilayers are grown on c plane sapphire substrates in a PA-MBE reactor whereby the doping of Nd is controlled by an effusion cell. GaN growth conditions and the Nd cell temperature control the incorporation of Nd within the matrix. The GaN epilayers were grown under nitrogen rich conditions, where reports in the literature suggest the best RE incorporation. Nitrogen rich growth does not yield the best quality material, and this was verified by x ray rocking curve data, with an average FWHM of ~1400 arcsec. The optical absorption characteristics are evaluated to ensure that the GaN:Nd epilayer remains transparent at the Nd emission wavelength of interest, 1064 nm. Two forms of room temperature pulsed PL spectra are collected: (1) by exciting the GaN matrix at 266 nm and (2) by exciting the Nd centers at 800 nm. The characteristic Nd spectra exhibit two groups of well-resolved peaks at room temperature. The Nd doping levels are measured by RBS and SIMS and correlated with the PL intensity. The highest PL intensities and unchanged absorption spectra correspond to a doping level of ~0.7 atomic percent. For the highest Nd cell temperature tested the RBS and SIMS data suggest that the Nd doping was ~5 atomic percent.

9:20 AM

BB4, Deep Level Transient Spectroscopy of AlGaN/GaN Heterostructure Treated by Fluoride-Based Plasma: *Liwu Lu*[1]; Yong Cai[1]; Lu Ding[1]; Weikun Ge[1]; Kei May Lau[1]; Kevin J. Chen[1]; [1]Hong Kong University of Science and Technology

Fluoride-based plasma treatment is a powerful technique that offers robust control over the threshold voltage, carrier density and gate Schottky barrier height in III-nitride field-effect transistors.[1,2] The technique also provides good device reliability and stability for practical implementations. In order to understand the underlying physics and evaluate the device reliability, it is important to investigate the energy levels associated with the fluorine ions in III-nitride materials. In this work, we carried out capacitance deep level transient spectroscopy on AlGaN/GaN heterostructure samples. By comparing the results from samples with and without fluorine treatment, the deep levels that are solely generated by the fluorine ions are identified.The Al0.3Ga0.7N/GaN heterostructure was grown on sapphire substrate by MOCVD. The thickness of Al0.3Ga0.7N barrier layer is 20 nm. Room temperature Hall measurements of the structure yield an electron sheet density of 1.3×10^{13} cm^{-2} and an electron mobility of 1000 cm^2/Vs. Circular Shottky barrier diodes (SBD) were fabricated using annealed Ti/Al/Ni/Au as cathode and Ni/Au as anode. Two types of SBD were prepared: one with the CF4 plasma treatment in the anode region before the metal deposition (sample W/T) and one without (W/OT). A Bio-Rad DL 8000 deep level transient spectroscopy was used to obtain DLTS spectra. The bias voltage, filling pulse voltage, filling pulse width were varied to profile the traps in the AlGaN/GaN heterostructures. The trap-related parameters, such as activation energy and capture cross section, were determined from an Arrhenius analysis based upon the Fourier analysis of transients collected as a function of temperature (up to 550 K). From the DLTS measurements carried out on the samples with and without the fluorine plasma treatment, we obtained the following results: 1) In the conventional baseline AlGaN/GaN structure without the plasma treatment, we observed three trap states with an energy level of 0.4 eV (E3), 0.61 eV (E1) and 0.9 eV (E2), respectively. E1 is related to the interface states, E2 is related to the bulk point defects (either in GaN or AlGaN) and E3 is likely related to the point defects in the AlGaN layer (surface or bulk). 2) In the sample with the fluorine plasma treatment, a strong signal is observed in the DLTS spectra at high temperature, indicating an additional deep level introduced by the fluorine ions. This deep level is at least 1.5 eV below the conduction band and acceptor-like. Reductions in densities of E2 and E3 traps are also observed, indicating that the fluorine plasma treatment may have the effect of suppressing the these traps in the AlGaN/GaN heterostructures. References: [1]Y. Cai, IEEE Electron Device Letters, vol. 26, pp. 435-437, 2005. [2]Y. Cai, IEEE Trans. Electron Devices, vol. 53, pp. 2207-2215, 2006.

9:40 AM Student

BB5, Characterization of Mg-Doped AlInN Annealed in Nitrogen and Oxygen Ambients: Yan-Kuin Su[1]; *An-Ting Cheng*[1]; Wei-Chi Lai[2]; Ying-Zhi Chen[1]; [1]National Cheng Kung University, Advanced Optoelectronic Technology Center, Institute of Microelectronics and Department of Electrical Engineering; [2]National Cheng Kung University, Institute of Electro-Optical Science and Engineering

III-nitride materials are excellent candidates for optoelectronic devices due to the wide range of direct band gaps and the high strength of bonding energies. Many efforts have been made to improve the film quality, device performance and reliability. For example, it was shown that AlGaN/GaN superlattices (SLs) structure could eliminate cracks as well as threading dislocations. The piezoelectric effect resulted from the lattice mismatch, however, could lead to a large shift of the absorption edge in the AlGaN/GaN SLs structure. In order to realize the nearly lattice-matched AlInN/GaN structures, the fabrication and characterization of p-type AlInN were demonstrated for the contact layer of GaN-based light emitting diode (LED) applications. Samples prepared in this study were grown by low-pressure metalorganic chemical vapor deposition on sapphire substrates. Trimethylaluminum (TMAl), trimethylindium (TMIn), and ammonia (NH3) were used as source materials for Al, In, and N, respectively. Bis-cyclopentadienyl magnesium (Cp2Mg) was served as p-type dopant precursor. The effects of thermal treatment in N_2 and O_2 ambients on the surface morphology and hole concentration of p-type AlInN were demonstrated. For the as-grown $Al_{0.79}In_{0.21}N$ doped with Mg, the measured root-mean-square (RMS) roughness was 2.202 nm by using atomic force microscopy (AFM). After the thermal treatment at 650°C for 15 min in the N_2 ambient, there was no significant change of the surface morphology with the RMS roughness of 2.511 nm. However, the tip-shaped AlInN was formed while the annealing temperature of 750°C was employed. When we use O_2 ambient gas for thermal treatment, on the other hand, rod-shaped AlInN was formed. The RMS roughnesses of AlInN samples annealed at 650°C and 750°C were 4.956 nm and 14.338 nm, respectively. In addition, the diameter and height of rods increased with the higher annealing temperature. Therefore, the ambient gas plays an important role in the determination of surface morphology of AlInN during the thermal treatment. In order to understand the effect of thermal treatment on the electrical properties of AlInN, van der Pauw geometry Hall measurement was performed at room temperature. It was found that AlInN was not p-type until the annealing temperature above 650°C. The sheet hole concentrations were 4.73×10^{12} and 5.12×10^{12} cm^{-2} for N_2 and O_2 ambient gases, respectively, at the annealing temperature of 750°C. Therefore, AFM and Hall measurement observations suggested that one can realize a p-type AlInN layer nearly lattice-matched to GaN by using the thermal treatment in N_2 and O_2 ambients. In addition, the surface morphology of p-type AlInN was influenced by the choice of ambient gas. The rod-shaped p-type AlInN may be a good candidate for improving the light extraction efficiency of GaN-based LEDs.

10:00 AM Break

10:20 AM Student

BB6, A Study of MgO and AlN Caps for Protecting the GaN Surface during Ultra-Fast Microwave Annealing: *Siddarth Sundaresan*[1]; Albert Davydov[2]; Elba Gomar-Nadal[3]; Ellen Williams[3]; Yonglai Tian[4]; Madhu Murthy[1]; Nadeemullah Mahadik[1]; Jaime Freitas, Jr.[5]; Syed Qadri[5]; M. Mastro[5]; Charles Eddy, Jr.[5]; R. Holm[5]; R. Henry[5]; R. Vispute[3]; M. Rao[1]; [1]George Mason University; [2]National Institute of Standards and Technology; [3]University of Maryland; [4]LT Technologies; [5]U.S. Naval Research Laboratory

The inability to obtain highly conductive p-type layers impedes the development of efficient GaN optical and high-power devices. Annealing temperatures > 1100°C are required for activating in-situ doped or ion-implanted acceptors in GaN, and for repairing the implantation-induced lattice damage. A novel microwave rapid thermal annealing (RTA) technique has been recently developed by the authors for annealing ion-implanted SiC at temperatures > 2000°C at ultra-fast temperature ramping rates of 500°C/s. However, GaN is prone to decomposition at temperatures as low as 800°C. To avoid thermal decomposition, GaN needs to be annealed in either high-pressure nitrogen-containing atmosphere, with rapid temperature ramping, and/or needs to be capped with inert capping layer.In this work, we extend the use of the microwave RTA technique for annealing capped Mg-doped GaN epilayers at temperatures > 1200°C for 5 s durations. A highly conducting 4H-SiC sample placed underneath the GaN sample of interest serves as the susceptor for heating the GaN sample, when both the samples are placed within the microwave heating head. Microwave anneals are performed with MgO, AlN surface capping layers and are compared to uncapped GaN anneals. 200 nm AlN layers are deposited on the GaN sample either by PLD or by e-beam evaporation. 200 nm MgO layers are deposited on the GaN using e-beam evaporation. The PLD AlN layers remained on the GaN surface even after 1500°C/5 s annealing; however they couldn't be removed using any chemical etchant. The e-beam evaporated MgO cap was thermally stable at 1400°C and could be easily etched in 0.1 M acetic acid. AFM images of an as-grown GaN sample, and 1300°C / 5 s annealed samples (Fig. 1), with and without the MgO cap indicate that the MgO capped sample surface closely resembles the as-grown sample and exhibits much smaller RMS roughness (0.9 nm) compared to the uncapped sample (9.2 nm). Several 20-30 nm deep pits are observed on the uncapped sample, indicating a significant decomposition/sublimation of GaN from these regions. Room-temperature (RT) Hall measurements indicate an increase in hole concentration from 1.3 x 10^{17} cm^{-3} for the as-grown sample to 3 x 10^{17} cm^{-3} for the MgO capped, 1300°C/5 s microwave annealing. Two dominant PL peaks (Fig. 2) at 2.91 eV and 2.97 eV, corresponding to the electrically-activated Mg dopant can be seen for the 1300°C/5 s annealed sample, indicating that the microwave anneal was successful in activating the Mg dopant. HR-XRD rocking curves for MgO capped anneal at 1400°C are ~23% narrower compared to uncapped annealing at the same temperature. Results on the e-beam deposited AlN cap will be compared with MgO-capped and uncapped GaN anneals.

10:40 AM Student

BB7, Comparative Study of As-Grown AlGaAs/GaAs/GaAs HBTs and Wafer Fused AlGaAs/GaAs/GaN HBTs: *Chuanxin Lian*[1]; Huili Xing[1]; [1]University of Notre Dame

Combining the advantages of both GaAs and GaN systems, heterojunction bipolar transistors (HBTs) based on AlGaAs(emitter)/GaAs(base)/GaN(collector) double heterostructures are promising candidates for high-speed, high-power microwave applications. DC current gain as high as near 10 has been reported recently by us in AlGaAs/GaAs/GaN HBTs formed by wafer fusion. [IEEE EDL 28(1): p.8, 2007] Compared with the as-grown AlGaAs/GaAs/GaAs HBTs, the fused devices exhibited large current gain degradation. To improve the device performance, it is essential to understand the underlying degradation mechanisms. Detailed comparison between as-grown and fused HBTs is of great importance, especially the adverse effect of high temperature annealing since it was employed in the wafer fusion process to strengthen the interface bonds between GaAs and GaN. In this work, as-grown AlGaAs/GaAs/GaAs HBTs were annealed at various temperatures that were the same in preparing the fused HBTs. Device I-V characteristics were then thoroughly compared among the as-grown, the as-grown annealed and the fused HBTs. To characterize the p-GaAs base, majority carrier concentration and minority carrier lifetime were measured by Hall measurement and transient absorption spectroscopy, respectively. Three AlGaAs/GaAs/GaAs annealed HBTs prepared from the same wafer were annealed at 450°C, 550°C and 650°C in N2 for one hour, respectively, with a GaAs wafer as the proximity cap. The AlGaAs/GaAs/GaN fused HBTs were fused at 550°C, 600°C and 650°C, respectively, in N2 ambient. An external pressure of ~ 5 MPa was maintained on the two wafers during the fusion process. It is found that the high temperature annealing can degrade the current gain of as-grown AlGaAs/GaAs/GaAs HBTs and the extent of degradation depends on the annealing temperature. Though the current gain drops largely after annealing at 550°C and 650°C, it is observed that high temperature treatment alone does not contribute to the total gain reduction by comparing the current gains of annealed and fused HBTs. Other possible degradation mechanisms such as internal strain, interface disorder and conduction band offset between GaAs and GaN are proposed as well. Annealing at 450°C has negligible effect on the current gain, which suggests that a low temperature fusion process be preferable to improve the fused device performance. The fused HBTs have much larger base-collector reverse leakage currents than as-grown HBTs, which is not attributed to the high temperature annealing. Instead, the non-uniformly fused defective interface is believed to be responsible for the large leakage current. It is also found that the breakdown voltage of as-grown HBTs is not affected by the high temperature annealing and that of the fused HBTs is expected to improve after fusion process optimization.

11:00 AM

BB8, Chemical Mechanical Polishing of GaN: *Sumiko Hayashi*[1]; Tommy Koga[1]; Mark Goorsky[1]; [1]University of California, Los Angeles

Chemical mechanical polishing (CMP) of gallium nitride to produce smooth, damage free surfaces has been demonstrated using a sodium hypochlorite (NaOCl) based solutions. Solutions using 70 nm alumina abrasive particles are able to planarize either Ga or N-face surfaces from greater than 15 nm RMS surface roughness down to 0.5 nm RMS surface roughness. MOVPE and MBE grown samples with different defect densities were used. Under 5 kPa of applied pressure and a plate rotation rate of 30 RPM the removal rate was found to be approximately 3 nm/min, similar to removal rates using colloidal silica slurries (P.R. Taverner et al, Electrochem. Solid-State Lett. (2002)) However, in this case the removal rate is not strongly dependant upon the polarity of the GaN indicating that the material removal is primarily mechanical in nature with the alumina/NaOCl slurry. Although mechanical (abrasive) material removal is desirable to achieve efficient planarization, crystalline damage of the surface is generally induced. High resolution x-ray diffraction was used to determine the extent of crystalline damage due to the CMP process. The amount of diffuse scatter in triple axis mode is very sensitive to surface and even sub-surface damage allowing a before and after CMP comparison. Crystalline damage can be detected after CMP, which is verified by small surface scratches visible with atomic force microscopy. The density and depth of surface scratches can be reduced by adding a surfactant. Additionally, this damage can be removed by polishing with an altered slurry where the abrasive alumina particles are eliminated. The removal rate is reduced substantially; however, damage free surfaces can be achieved.

11:20 AM

BB9, Cleaved Nitride Semiconductor Laser Mirrors: Yi-Cheng Chang[1]; *Wei-Li Chen*[1]; Che-Chin Chen[1]; Ming-Hua Lo[2]; Tien-Chang Lu[2]; Jong-Ching Wu[1]; [1]National Changhua University of Education; [2]National Chiao Tung University

It is challenging to fabricate nitride laser mirrors on foreign substrates due to the lack of naturally cleaved facets. We demonstrate smooth cleaved gallium nitride facet mirrors on Si(111) substrate fabricated by a micro-cleaving technology. The cleaved surfaces follow the crystallographic direction of the nitride crystal. The fabrication of laser facets on a full wafer scale with precise control on mirror position can be achieved. The resonance characteristics of a Fabry-Perot laser such as threshold current density and slope efficiency will be drastically affected if both end reflectors are not smooth. The approach demonstrated in this study can be applied to sapphire substrates. A micro-cleaving approach was applied to create smooth facet mirrors. Designed cantilever features on a gallium nitride thin film were defined by photolithography, followed by a photo enhance electrochemical (PEC) etch until the substrate was exposed. Lateral undercuts underneath the patterned features were created by isotropic wet etch of the silicon substrate. The designed nitride suspended cantilevers were isolated from the substrate completely. Small notches were located near the fixed end of the hung cantilevers to facilitate the micro-cleaving process by concentrated stress. Mechanical forces were applied to break the cantilevers. GaN based laser mirrors fabricated by directly cleaving sapphire and GaN substrates were compared. The facets made by micro-cleavage showed improved roughness confirmed by surface morphology characterization.

11:40 AM

BB10, Late News

Session CC:
Compound Semiconductor Nanowires

Friday AM	Room: 155
June 22, 2007	Location: DeBartolo Hall

Session Chairs: Hou Ng, Hewlett-Packard Company; Kris Bertness, National Institute of Standards and Technology

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8:20 AM

CC1, III-V Nanowire Growth Mechanism: VLS or VSS: *Shadi A. Dayeh*[1]; Paul K. L. Yu[1]; Edward T. Yu[1]; Deli Wang[1]; [1]University of California, San Diego

III-V compound semiconductor nanowires (NWs) are of outstanding current interest for potential applications in electronics and optoelectronics because their electronic and optical properties can be tuned via appropriate materials selection including alloy and heterostructure formation. To realize their full potential, thorough understanding of the NW growth mechanism and rational control over the NW growth morphology and properties are essential. While most prior reports on metal assisted NW growth invoke the Vapor-Liquid-Solid (VLS) mechanism,[1] recent studies on Au-assisted growth of III-V NWs proposed a Vapor-Solid-Solid (VSS) growth mechanism based on the observation of growth cessation at temperatures higher than the Au-In/Ga alloyed particle melting point.[2] In the presence of SiO$_x$ on the growth substrate and without any metal particle, Oxide Assisted[3] and Si-Assisted[4] III-V NW growth were also proposed. In this presentation, we report detailed studies of the growth of InAs NWs on InAs(111)B substrates using metal-organic chemical vapor deposition (MOCVD). Our results reveal that surface kinetics, influenced by both growth temperature and the input V/III ratio, play a dominant role in NW growth: (1) using V/III=60, NW growth ceases at T≈510°C, similar to that reported by Dick et. al.;[2] however, for V/III=7.5, NW growth ceases only for T≥560°C. At a higher V/III ratio, liquid In reacts with available As, which impedes In diffusion on the substrate surface, and results in a 2D growth. As a result, liquid In is depleted from the NW growth sites and the NW growth rate decreases, which was consistent on InAs and SiO$_2$ surfaces. Indeed, the NW growth rate and nucleation density for both, InAs and InP NWs, increase at a lower input V/III ratio. Consequently, we conclude that the NW growth morphology is determined by both the input V/III ratio and substrate temperature. On the other hand, without Au nanoparticles or SiOx layer on the growth substrate, vertical InAs NWs can be nucleated from In droplets and grow on InAs(111)B surfaces when excess liquid In can be maintained throughout the growth experiment. The nucleating In droplets can be consumed during the growth as evident by the decreasing size of In droplets at the tips of longer NWs. These results strongly support the VLS growth mechanism for III-V NWs and enable improved control over their morphology. References: [1]Wagner, R. S.; Ellis, W. C. Appl. Phys. Lett. 1964, 4, 89. [2]Dick, K. A.; Deppert, K.; Martensson, T.; Mandl, B.; Samuelson, L.; Seifert, W. NanoLetters 2005, 5, 761. [3]Mandl, B., Stangl, J., Martensson, T., Mikkelsen, A., Eriksson, J., Karlsson, L. S., Bauer, G., Samuelson, L., Seifert, W. Nanoletters 2006, 6, 1817. [4]Park, H. D., Prokes, S. M., Twigg, M. E., Cammarata R. C., Gaillot, A.-C. Appl. Phys. Lett. 2006, 89, 223125.

8:40 AM Student

CC2, V/III Ratio Effects on the Shape and Optical Properties of InP Nanowires Grown on Silicon: *Michael Moewe*[1]; Linus Chuang[1]; Shanna Crankshaw[1]; Connie Chang-Hasnain[1]; [1]University of California at Berkeley

III-V nanowires (NWs) grown on silicon are promising for CMOS integration due to their lower growth temperatures (400-500°C) and tolerance of large lattice-mismatches. Recently, we have grown III-V NWs with excellent optical properties using MOCVD. Here we report the effect of varying the MOCVD gas precursor V/III ratios on the structural and optical properties of InP nanowires grown on (111)Si susbstrates. The morphological variation with V/III ratio implies tailorability. For an optimum ratio, uniform diameter NWs result, with extremely narrow photoluminescence (PL) peaks strongly blue-shifted from the InP bulk emission due to quantum confinement. InP NW samples were grown on (111)Si with V/III ratios of 15, 30, 67, 183 and 240. Au nanoparticles were used as vapor-liquid-solid (VLS) growth catalysts. The lowest V/III ratios generated sparse, stout structures. At a V/III ratio of 67, uniformly straight NWs grew with much higher density. Increasing the V/III ratio to 183 and 240 yielded progressively more tapered NWs due to strong sidewall deposition. Micro-PL characterization was performed at room temperature and 4 K. At room temperature, the distinct NWs grown at V/III = 67 shows a strong blueshift in the PL peak from 1.39 eV to 1.44 eV. The PL intensity on the blue side of the more tapered NW ensemble (V/III=183 and 240) is comparatively lower, possibly indicating emission from the wider base of the structure, with reduced quantization. At 4 K, emission from the sample with V/III = 15 is least intense and lies at the bulk InP peak (1.423 eV). For V/III = 30, the intensity increases by a factor of eight. The PL peak of the V/III = 67 sample with straight NWs blueshifts by 40 meV from the bulk InP peak due to quantum confinement. Single-wire peaks from the narrowest NWs are visible on the high-energy side of the ensemble spectrum. A peak with a 178 meV blueshift and linewidth of 1.4 meV was observed, the narrowest reported for a III-V NW. For higher V/III ratios, the high-energy fine spectral features disappear due to the increased NW base diameter, consistent with the room temperature trend. As excitation power increases, the 4 K PL wavelength blueshifts. The straight and tapered NWs show a blueshift of 9 meV and 40 meV, respectively, over a 1000X increase of excitation power. The large blueshift for the tapered NWs is attributed to the effect of decreased carrier diffusion at higher pumping, resulting in emission from the narrower part of tapered NWs. In addition, the PL intensity vs. pump power behavior is significantly different for tapered wires at both RT and 4 K. This luminescence efficiency increases with pump power for tapered wires. This effect is currently under investigation.

9:00 AM Student

CC3, Photocurrent Polarization Anisotropy of Randomly Oriented Nanowires Network: *Yanghai Yu*[1]; Vladimir Protasenko[1]; Aidong Lan[1]; Masaru Kuno[1]; Prashant Kamat[1]; [1]University of Notre Dame

Due to one dimensional nature of semiconductor nanowires (NWs), the generated photocurrent strongly depends on the orientation of light polarization with respect to the NWs axis. Unexpectedly, we discovered that the arrays of randomly oriented NWs also exhibit the polarization sensitivity, which is primarily determined by the orientation of electrodes connected to NWs. We studied this phenomenon for CdSe and CdTe NWs (5-15 nm diameters) placed in between Au electrodes separated by 30-100 μm wide gaps. High TEM resolution images show that the wires are highly crystalline, thin, with the lengths between 1 μm and 10 μm. With the Au contacts formed on the top of NW layer, we detected the maximum current when the light polarization is normal to the electrodes. In addition, Photocurrent anisotropy defined as $\rho=(I_{max}-I_{min})/(I_{max}+I_{min})$ varies with the distances from the electrodes, and for example, for CdSe NWs ρ decreases from ~20% near the electrodes to 5-11% in the middle of the gap. In contrast, CdTe NWs networks exhibits stronger anisotropy in the middle of the gap compared with ρ~25% near the electrodes. We believe that this trend is associated with typically longer CdTe NWs lengths compared with CdSe counterparts. But in both cases, the maximum photocurrent is observed for excitation polarization normal to the electrodes. In our studies, we also explore the photocurrent anisotropy dependence on the voltage, gap width and wire coverage, and our research demonstrates the possibility of building polarization sensitive devices based on randomly deposited NWs.

9:20 AM

CC4, Growth and Characterization of Vertically Aligned III-Nitride Nanowires and Heterostructure Nanowires: George Wang[1]; *Qiming Li*[1]; A. Alec Talin[1]; J. Randall Creighton[1]; Donald Werder[2]; Elaine Lai[1]; Richard Anderson[1]; Ilke Arslan[1]; [1]Sandia National Laboratories; [2]Los Alamos National Laboratory

Nanowires based on the direct bandgap semiconductor Group III nitride (AlGaInN) materials system have attracted attention as potential building blocks in optoelectronics, sensing, and electronics. We have employed a VLS-based metal-organic chemical vapor deposition process to synthesize highly aligned arrays of single-crystalline GaN nanowires on 2-inch diameter sapphire and GaN substrates without the use of a patterned template. SEM and TEM analysis indicate that the nanowires share a common [11-20] growth orientation and have aligned facets. The effects of growth time and catalyst preparation, including the use of both thin metal films and solution-based catalysts, were both found to have strong effects on the ordered growth and will be discussed. Optical and electrical characterization of the nanowires were also performed, and show a strong correlation between growth temperature and the optical and electrical properties, which we propose is due to carbon incorporation from the metal-organic source. Building on our growth technique, aligned radial heterostructure nanowire arrays consisting of GaN cores and various III-nitride shell materials, including AlGaN and AlN, were synthesized and characterized. Our results show that the presence of the AlGaN and AlN shell layers in the core-shell nanowires have significant effects on the nanowire transport properties, when compared to pure GaN nanowires. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

9:40 AM

CC5, Mechanical Properties of C-Axis Oriented Gallium Nitride Nanowires: *Shawn Tanner*[1]; Jason Gray[1]; Charles Rogers[1]; Kris Bertness[2]; Paul Blanchard[2]; Norman Sanford[2]; [1]University of Colorado at Boulder; [2]National Institute of Standards and Technology

We have measured room temperature mechanical resonance frequencies and mechanical quality factors, Q, of c-axis oriented Gallium Nitride (GaN) nanowires. Mechanical Q values, defined as the resonance frequency divided by the full width at half maximum power, in excess of 30,000 are common with some in excess of 50,000. GaN material is piezoelectric and piezoresistive and therefore is an attractive material for nanoscale electromechanical devices. Small-diameter smooth surface GaN nanowires are single crystal nano-scale structures useful for testing material limits and device concepts. The GaN nanowires were grown at NIST in a gas-source molecular-beam epitaxy (MBE) system. The nanowires are grown on Si(111) substrates with 50-80 nm of aluminum nitride buffer layer. The growth procedure leads to the spontaneous formation of GaN nanowires without the need for metal catalysts. The nanowires grow oriented along the GaN c-axis and normal to the substrate surface and exhibit typically hexagonal crossections. Nanowires with diameters of 35 nm to 0.5 µm and length from 2 to 20 µm have been produced. The resonance line shapes of the lowest frequency singly clamped cantilever mode of the nanowires were measured for the as grown nanowires using the electron beam of an SEM to stochastically drive and measure the mechanical resonance. The typical dimensions of the measured nanowires were from 6-10 microns long and 35-100 nm in diameter. The fundamental resonance frequencies range from 400 kHz to 2.5 MHz. Estimates for the effective Young's Modulus are near 300 GPa and show an increasing value with increasing nanowire diameter. The deposition of contamination on the nanowire during the electron beam studies causes a time-dependent shift in the resonance frequency during the measurement and an associated apparent broadening of the resonance line shape making the measured Q a lower limit. Under certain circumstances, this technique produces driven oscillations resulting in apparent Q's that are frequently in excess of 250,000. We are also studying harvested nanowires attached to electrical contacts on substrates to investigate the mechanical and piezoresistive properties of nanowires in device geometries.

10:00 AM Break

10:20 AM

CC6, Correlation of Luminescence, Electrical Transport, and Growth Temperature for Individual GaN Nanowires: *Alec Talin*[1]; George Wang[1]; Elaine Lai[1]; Richard Anderson[1]; Randy Creighton[1]; Ilke Arslan[1]; [1]Sandia National Laboratories

Despite impressive progress in the synthesis of semiconductor nanowires, the systematic electrical and optical characterization of these nanostructures remains a formidable challenge, and the majority of data on nanowire transport published to date is based on one or a few individual devices fabricated using slow and painstaking direct-write electron or focused ion beam methods. In this paper, we describe a platform based strictly on optical lithography, and optimized for combined electrical and optical characterization of nanowires on an individual basis. We use this platform to correlate photoluminescence, electrical transport and substrate temperature for MOCVD-VLS grown GaN nanowires. Our platform consists of arrays of individually addressable interdigitated electrodes with gaps ranging from 1µm to 4 µm, and which are patterned over nanowires that are randomly dispersed on Si/SiO$_2$ substrates. The nanowires are characterized using a modified probe station, where a He-Cd laser, a spectrometer, and UV reflective optics have been interfaced with the probe station optical microscope. Our results to date indicate that as the substrate (sapphire or Si) temperature is increased from 800°C to 900°C, the nanowire resistivity drops from 10^4 ohm-cm to 10^{-2} ohm-cm, while the ratio of yellow to band edge luminescence decreases from ~1 to <0.1. Our results suggest that carbon, incorporated from the trimethyl gallium precursor, acts as a deep acceptor, compensating the intrinsic donors in the GaN nanowires, leading to high resistivity and increasing the ratio of yellow to band edge luminescence. This hypothesis is supported by the fact that the resistivity of VLS grown GaN nanowires without carbon bearing precursors, but otherwise with the same <11-20> orientation and high crystalline quality, is not very sensitive to substrate temperature in the range of 800°C to 900°C.

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.

10:40 AM

CC7, Time-Resolved and CW Photoluminescence Measurements on Strained and Unstrained GaN Nanowires Grown by Catalyst-Free MBE: *John Schlager*[1]; Norman Sanford[1]; Kris Bertness[1]; Paul Blanchard[1]; Lawrence Robins[1]; Beau Burton[2]; Steven George[2]; [1]National Institute of Standards and Technology; [2]University of Colorado at Boulder

Time-resolved and continuous-wave (cw) photoluminescence (PL) measurements were performed on GaN nanowires grown by catalyst-free molecular beam epitaxy on Si(111) substrates. As grown, the wires were 5-25 µm in length, c-axis oriented, and 30-100 nm in diameter. Before being tested, nanowires were prepared via three methods: 1) nanowires were randomly dispersed onto quartz substrates with metal reference grids to enable PL measurements on individual wires; 2) nanowires were made into bridge structures, with each dielectrophoretically-aligned nanowire spanning a pair of raised metal contacts; 3) randomly dispersed nanowires were conformally coated with aluminum oxide (Al$_2$0$_3$) using atomic layer deposition (ALD). These different nanowire treatments introduced varying amounts of strain that became evident in the shifted PL spectra at different temperatures. At base temperatures (~ 5 K), the shorter (< 6 µm) randomly-dispersed nanowires produced PL spectra with the dominant donor-bound exciton D^0X_A peak at 3.472 eV (corresponding to strain-free GaN) and a linewidth of 5 meV FWHM. The longer (greater than 10 µm in length) randomly-dispersed nanowires exhibited increasingly red-shifted PL peaks and spectral broadening with cooling. At base temperature, the dominant PL peak position for these wires was typically 3.462 eV. However, the as-grown c-axis and a-axis lattice constants for these wires, measured with x-ray diffraction, matched those of unstrained GaN. This suggests that the PL shift is due to a differential thermal contraction between the dispersed (and fixed) GaN nanowires and the quartz substrate – the net result leading to a tensile strain of the nanowires upon cooling. Similarly, PL revealed temperature-dependent tensile strain in the cooled nanowire bridge structures. Nanowires treated with an ALD Al$_2$0$_3$ coating, on the other hand, experienced compressive strain in both the c-axis and a-axis directions. X-ray diffraction measurements revealed a reduction in both the c and a lattice constants (Δc = - 0.002 and Δa = - 0.004 angstroms). PL measurements showed a blue shift in the dominant spectral peak as well as spectral broadening. The observed spectral shift is consistent with the strain theory of GaN. Time-resolved PL (TRPL) measurements of randomly-dispersed nanowires were made at 267 nm. Lifetimes of the dominant peaks at ~295 K (at ~5 K) ranged from < 0.3 ns to 0.93 ns (< 0.3 ns to 0.6 ns). Multi-photon PL and TRPL measurements at 800 nm yielded cw and temporal results that were similar to those with above-bandgap pumping. Strong waveguiding and lasing was observed in the longer nanowires. This work shows that PL and nanowire post processing can aid in better understanding strain states in GaN nanowires.

11:00 AM

CC8, Persistent Photoconductivity Studies of GaN Nanowires and Nanowire Bridge Structures: *Norman Sanford*[1]; Paul Blanchard[1]; Kristine Bertness[1]; Alexana Roshko[1]; Beau Burton[2]; Lorelle Mansfield[1]; John Schlager[1]; Steven George[2]; [1]National Institute of Standards and Technology; [2]University of Colorado

Room temperature persistent photoconductivity (PC) was measured on c-axis GaN nanowires that were grown by nitrogen plasma assisted MBE on Si(111) substrates. Nanowires were harvested from growth substrates and dispersed onto quartz plates. Two-terminal PC test structures were fabricated by: 1) Making ohmic contacts to the ends of the dispersed wires; 2) Suspending wires between ohmic metal stacks using dielectrophoretic alignment methods thereby forming electrically conducting nanowire bridges. In both cases the length of a wire between the ohmic pads was approximately 3 µm. Field-emission scanning electron microscopy revealed that the structures consisted of single uniform wires with diameters ranging from 50 to 100 nm, or larger diameter nanonowire clusters composed of several wires grown together. When illuminated (above gap) at 360 nm at ~3 mW/cm^2 and biased at 1V, the typical photocurrent for the single uniform wires increased immediately (1s sampling interval) from ~10 pA (in the dark) to ~0.2 uA and would return to this dark level after a few minutes when the illumination was blocked and the bias maintained. The spectral dependence of the PC generally showed abrupt band-edge onset with no significant conductivity (compared to the dark) for excitation below gap (500-600 nm). Under the same 1V bias, the thicker multi-wire clusters generally showed dark currents in the range of 0.1 uA – 1uA which increased roughly 10-fold when illuminated at 360 nm (~3 mW/cm^2). With the bias maintained but the light blocked, the current in these thicker multi-wire clusters would often persist for several hours before returning to their dark levels. The wire clusters under 1V bias could exhibit ~0.2 uA of photocurrent when illuminated below gap at 600 nm and this current persisted for ~ 3 h in the dark. Experiments attempting to determine the optical polarization dependence of the wire PC were inconclusive. Atomic layer-deposition was used to conformally deposit ~10 nm of amorphous alumina on the bridges. Under a 1V bias and 360 nm illumination these coated bridges showed a roughly ten-fold increase in photocurrent (compared to the uncoated cases) for all bridges examined. With the light blocked and the bias maintained, this persistent current seldom dropped below 1 uA after 20h for both single wires and the wire clusters. The results suggest that midgap defect states and traps associated with grain boundaries in the wire clusters contribute to the persistent PC and the below-gap PC, and that traps were also introduced by the oxide coating. Ongoing work examining the effects of other (non-oxide) ALD films, and correlating PC results with photoluminescence, will also be presented.

11:20 AM Student
CC9, Effects of Surface Fixed Charges and Interface Trap Charges on Transport Properties of InAs Nanowire Transistors: *Qingling Hang*[1]; Fudong Wang[2]; Patrick Carpenter[1]; Dmitry Zemlyanov[1]; William Buhro[2]; David Janes[1]; [1]Purdue University; [2]Washington University

Compared with 3-D and 2-D materials, 1-D nanowires have huge surface-to-volume ratio, which implies that surfaces of nanowires may have a large impact on nanowire device performance. Studies of nanowire surface effects can help to explain studies from various groups and will lay a foundation for many possible applications of nanowire devices, including sensors. A controlled nanowire surface will be a key to real world sensing applications in order to provide high sensitivity of large dynamic range and high selectivity from the controlled surface. However, up to now there has been a lack of surface study of nanowire transport properties in terms of surface charges, which can be fixed charges or interface trap charges. As to interface trap charges there are four different types of trap states, which are electron trap states, electron donor states, hole trap states and hole acceptor states. InAs nanowires were grown by a solution-liquid-solid (SLS) method and passivated with either ligands used in growth or 1-octadecanethiol (ODT). The field effect mobilities, i.e. the values extracted from measured I-V curves and estimated capacitance without considering surface states, are 1480 cm^2/Vs and 2470 cm ^{2}/Vs for the unpassivated and ODT-passivated wires, respectively. X-ray photoelectron spectroscopy studies of ODT-treated nanowires also confirm that the ODT molecules are bound to InAs nanowires through In-S bonds. It is believed that these molecules help to passivate the surface states on the InAs nanowires so that the Fermi level at the nanowire surface is not pinned in the conduction band. This is the reason why we can observe p channel conduction from both Cd doped InAs nanowires and ODT passivated InAs nanowires. Also the reduction of surface states on the nanowire surface means less scattering of the body electrons from the surface states, which may explain the mobility improvement after ODT passivation. MEDICI simulations of 20 nm undoped InAs nanowire transistors before and after passivation by ODT molecules have been used to understand the effects of surface states. Simulations representing best-fits to the measured data indicate that the ODT passivation reduces the effective nanowire/gate oxide donor trap density from 1.5E13/cm^2eV to 7E12/cm^2eV. The fixed charges at this interface, and the trap density at the exposed nanowire surface also decrease upon passivation. The fixed charges are mainly responsible for threshold voltage shifts. However the fixed charges on exposed nanowire surface contribute to the subthreshold slope change of the Ids/Vgs curves. The simulation also indicates that the mobility of electrons in the body of nanowire increases from 2200 cm^2/Vs to 4000 cm^2/Vs, which implies that the reduction of interface trap states help to reduce the scattering of body electrons considering the de Broglie wavelength of electrons in InAs 40 nm.

11:40 AM Student
CC10, Enhancement of Carrier Mobility in Semiconductor Nanostructures Using Dielectric Mismatch Effect: *Aniruddha Konar*[1]; Debdeep Jena[1]; [1]University of Notre Dame

Long ago Keldysh[1] predicted a giant improvement of the excitonic binding energy for freestanding nanoscale semiconductor structures such as nanowires[2,3] and nanomembranes due to the dielectric mismatch between the nanostructure and the surrounding environment. Though the optical properties of 1D and 2D semiconductor structures has been investigated both theoretically and experimentally, the effect of the dielectric mismatch on the electronic transport properties of nanostructures has not received as much attention. In an ultrathin free-standing quantum wire or a thin nanoscale membrane, most of the field lines originating from Coulombic impurities (such as shallow dopants) leak out into the surrounding environment. The scattering potential experienced by electrons moving along the axis of the nanostructures is damped, and hence the electron mobility is strongly affected by the surrounding environment. We show that[4] - a) by coating the nanostructures with high-K dielectrics, scattering of carrier electrons from Coulombic impurities can be strongly damped, resulting in a substantial improvement in mobilities of carriers, b) free-standing nanostructures (nanowires, nanotubes, and nanomembranes surrounded by air) will suffer from enhanced scattering and lower mobilities due to image charges of impurities formed as a result of dielectric mismatch between air and the semiconducting material, and c) the availability of high-K dielectrics imply that a drastic improvement of electron mobility in devices such as nanowire and nanotube transistors is possible, which will result in a better control of power dissipation and switching speed by 'dielectric engineering'. Fermi's-Golden rule enables us to calculate Coulombic scattering rates for electrons. The enhancement in mobility occurs predominantly due to a large damping of impurity Coulombic scattering potential. When the environment dielectric constant is changed from 1 (air) to 100 (high-k oxide dielectric), the Coulomb scattering rate is decreases from 700/ps to 4/ps for a GaAs nanowire (1nm radius), and from 66/ps to 3/ps for a 2D GaAs nanomembrane (1nm thicknes). When other scattering mechanisms (surface roughness, phonon scattering) are considered, we find that the total electron mobility of the semiconductor nanostructures can be enhanced by 1-2 orders of magnitude by coating them with high-k dielectrics. We find that this enhancement of conductivity happens if the characteristic dimension of the nanostructure is smaller than the effective Bohr radius. Thus, "dielectric engineering of nanostructures" can be used as an effective technique for improving mobilities in bottom-up grown semiconductor nanostructures, similar to modulation doping in epitaxial heterostructures. References: [1]L.V. Keldysh, JETP Lett. 92, 568, 1979. [2]E.A. Muljarov et. al, Phys. Rev. B, 62, 7420, 2000. [3]L.V. Keldysh, phys. stat. sol. (a), 164, 3, 1997. [4]D. Jena & A. Konar, Phys. Rev. Lett, to appear, 2007.

Session DD:
Narrow Gap Materials and Devices

Friday AM	Room: 131
June 22, 2007	Location: DeBartolo Hall

Session Chairs: Christine Wang, Massachusetts Institute of Technology, Lincoln Laboratory; L. Ralph Dawson, University of New Mexico

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8:20 AM
DD1, Long-Wavelength Light Emitters on Lattice-Engineered GaAs Substrates: *Kenneth Lee*[1]; Eugene Fitzgerald[1]; [1]Massachusetts Institute of Technology

Devices for telecommunications applications at 1.3 and 1.55 μm have traditionally been grown on InP substrates. There is motivation to grow such devices on GaAs substrates, because of the availability of larger wafer sizes and more modern wafer processing equipment, which would lead to increased device yields and thereby lower costs. By using metamorphic compositionally-graded InGaAs buffers starting on GaAs substrates, it is possible to create virtual substrates with lattice constants intermediate to those of GaAs and InP. Light emitters designed for telecommunications applications can be grown on such virtual substrates entirely in the InAlGaAs material system, which has the potential for larger band offsets and hence electronic confinement, as well as better refractive index contrast for improved optical waveguiding, compared to conventional devices. We report on the growth of high quality $In_xGa_{1-x}As$/GaAs virtual substrates using MOCVD, which have final relaxed lattice constants of 5.793 Å, corresponding to $x = 0.346$. The entire graded buffer was grown at 700°C, and the final TDD was found to be $< 9.5 \times 10^4$ cm^{-2}. Both doped and undoped InAlAs/InAlGaAs/InGaAs quantum well (QW) separate confinement heterostructures (SCHs) were regrown on the buffers. Cross-sectional TEM was performed and confirmed the flatness and high quality of the QW and other device layers. Room- and low-temperature photoluminescence (PL) measurements were carried out on the structures. Emission wavelengths at room temperature ranged from 1.23 to 1.46 µm as the amount of compressive strain in the QW was increased, with full-width-at-half-maximum (FWHM) values as low as 1.9 kT. Work is ongoing to fabricate and characterize optical devices made of the material described in this work.

8:40 AM

DD2, Electric Field and Size Dependence of Magnetic Field Sensitivity in an InAs 2-DEG: *Thomas Boone*[1]; Liesl Folks[1]; Jordan Katine[1]; Ernesto Marinero[1]; Neil Smith[1]; Bruce Gurney[1]; [1]Hitachi Global Storage

We report the effects of large electric fields and impact ionization on the performance of structures fabricated from quantum wells in type II heterostructures of AlSb/InAs/AlSb, which have been developed[1] for a variety of conventional microelectronic devices (e.g. HEMTs, RTDs, etc). We find in Hall crosses with characteristic width larger than 300nm that the increase in velocity with increasing electric field slows considerably as impact ionization appears to raise the carrier concentration. Due to the high electron mobility and saturation drift velocity of the InAs 2-DEG, there is increasing interest in this material system for magnetic field sensors such as extraordinary magnetoresistive (EMR) devices.[2] EMR devices are comprised of a hybrid metal/semiconductor conduction channel and exploit the Lorentz force to selectively steer the current between the metallic and semiconducting regions. This shared conductance results in a non-local resistance change that is proportional to the amplitude and polarity of the external magnetic field applied perpendicular to the 2-DEG. For high performance applications EMR devices will need to operate at high current densities. Previously, Brar et al. reported that 10 µm channel wide HEMTs made from these heterostructures suffered from poor performance due to impact ionization within the channel at modest drain source voltages;[3] we have investigated the size and electric field dependence of Hall cross and EMR devices. Hall crosses have been fabricated from AlSb(2nm)/InAs(12.5nm)/AlSb(2nm) quantum wells with lateral dimensions ranging from 300 nm to 1 µm. These structures have been characterized at 300 K in magnetic fields approaching 1000 Gauss. Bias voltages up to 1V have been applied resulting in current densities beyond 1×10^7 A/cm^2. Average electron drift velocity and carrier concentrations are calculated directly from the current and Hall voltage measurements. Consistent with impact ionization, carrier concentration within the channel begins to increase monotonically as the applied voltage increases beyond 0.2 V. The average electron drift velocity initially increases linearly with applied voltage. However, once significant carrier generation begins the drift velocity dependence on voltage slows considerably and appears to saturate. This transition occurs at drift velocities of only $1\text{-}3 \times 10^7$ cm/sec, which is lower than the predicted saturation drift velocity for InAs of 2×10^8 cm/sec.[4] Therefore, this behavior implies that the generated carriers begin populating a lower mobility channel. Analysis of the various scaling effects, as well as the consequences for Hall sensors and EMR devices will be discussed. [1]H Kroemer, Physica E: Low-dimensional Systems and Nanostructures v20, n3, p193, 2003. [2]T. Boone et al., IEEE Trans. Mag, 42, 3270, 2006. [3]Brar, B. Kroemer, H., Electron Device Letters, v16, n 12. 1995. [4]K. Brennan and K. Hess, Solid-State Electron., v27, n4, 1984.

9:00 AM

DD3, Comparison of MBE Growth of InSb on Si (001) and GaAs (001): Lien Tran[1]; Fariba Hatami[1]; *W. Masselink*[1]; [1]Humboldt University Berlin

The replacement of native oxides with deposited oxides in CMOS technology opens the door to replacing the Si with semiconductors without high-quality native oxides. For example, the use of InSb in logic applications could allow much lower operating voltages and power dissipation due to the InSb channels reaching saturation at significantly lower electric fields. Epitaxy of InSb onto Si could be done directly or using an intermediate layer such as GaP, GaAs, or InP. In the current work we describe the growth of InSb on both Si (001) and GaAs (001) using MBE and compare the growth and properties of the resulting InSb films. Growth was carried out using a Riber Compact 21T MBE system and a Veeco valved cracker cell for Sb. The growth on GaAs was initiated after standard oxide desorption and the substrate temperature was decreased to 300°C. InSb was deposited at this temperature with a Sb/In flux ratio of about 5 and a growth rate of 0.2 nm/s. Typically the RHEED pattern establishes a 2x4 pattern after about 10nm and after 60nm the substrate temperature is raised to the end growth temperature of between 340 and 420°C. In all cases, mirror-like surfaces result. The complete 2µm films were characterized in terms of background electron concentration, mobility, and x-ray r°Cking curve width. Our best results are for a growth temperature of 350°C, resulting in room-temperature mobility of 41000 cm^2/Vs. Growth on Si (001) was similar to that on GaAs. Vicinal Si(001) substrates offcut by 4° toward [110] were prepared by repeated oxidation and oxide-removal and then loaded into the MBE system. After the substrate temperature had been increased to about 820°C, the surface shows a clear 2x4 reconstruction and appears to be free of oxide. This reconstruction remains until the substrate temperature reaches $T_s = 1015$°C, at which temperature a 2x1 appears, indicating a dominance of double-height steps. After allowing the substrate to cool to the intended growth temperature for InSb, it is exposed to cracked Sb, resulting in the surface going from 2x1 to 1x1. This 1x1 reconstruction remains throughout the subsequent InSb deposition. We have investigated growth temperatures between 300 and 420°C for growth on Si(100). In contrast to growth on GaAs, the best results have been achieved at the high end of the range of Ts = 420°C, resulting in a mobility of 26000 cm^2/Vs for a 2µm film.

9:20 AM Student

DD4, Capacitance-Voltage Characterization of InSb MOS Structures with ALD High-k Gate Dielectrics: *Tian Yang*[1]; Yi Xuan[1]; Peide Ye[1]; Weike Wang[2]; J. C. M. Hwang[2]; D. Lubyshev[3]; J. M. Fastenau[3]; W. K. Liu[3]; T. D. Mishima[4]; M. B. Santos[4]; [1]Purdue University; [2]Lehigh University; [3]IQE Inc.; [4]University of Oklahoma

With the official announcement from Intel and IBM to implement atomic-layer-deposited (ALD) high-k gate dielectrics and metal gates in high-volume manufacture of their 45-nm CMOS ICs,[1] optimism is spread across the research community about novel channel materials for future ultimate CMOS ICs. With the elimination of SiO_2 as the gate dielectric for the channel surface, one of the most important advantages of Si over compound semiconductors vanishes. There is a growing hope that, with ALD high-k dielectrics developed for Si maybe applicable to compound semiconductors. In particular, with an electron mobility as high as 77,000 cm2/Vs, InSb is one of the most promising compound semiconductors. However, research on high-k gate dielectrics for InSb is rare[2]. We present a systematic capacitance-voltage (C-V) study, for the first time, of ALD- Al_2O_3/n-InSb MOS devices with InSb grown on semi-insulating GaAs by molecular beam epitaxy (MBE), where the oxide is directly grown on semiconductor channel material. After MBE, the InSb surface was treated with different wet chemicals such as HCl and NH_4OH, before thin Al_2O_3 films were deposited by ALD at 200°C. After ALD, the Al_2O_3 was annealed between 300°C and 400°C in N_2 to improve its bulk and interface properties. C-V characteristics were then measured on the MOS diodes between 80 K and room temperature and between 1 kHz and 10 MHz. The room-temperature accumulation capacitance exhibits little dispersion between 1 kHz and 1 MHz. However, due to the narrow bandgap of InSb and high minority carrier (hole) concentration at room temperature, the room-temperature C-V characteristic at 1 MHz differs significantly from that at 10 MHz. This difference vanishes at 88 K when the holes are quenched. According to the difference between low-frequency and high-frequency C-V characteristics, the mid-gap interface trap density (Dit) was calculated to be 4-7X10E11/cm^2-eV. More detailed analysis and experiments, particularly with lower- temperature ALD Al_2O_3 and HfO_2 on InSb, are ongoing. [1]http://www.intel.com/pressroom/archive/releases/20060125comp.htm. [2]S. Datta, et al., IEDM Tech. Dig., 783 (2005).

9:40 AM Student

DD5, Thermally Stable Gate Metallizations for Antimonide-Based High Electron Mobility Transistors with Indium Arsenide Channels: *Trevor Buehl*[1]; Robert Dormaier[1]; Bangzhi Liu[1]; Qi Zhang[1]; Suzanne Mohney[1]; [1]Pennsylvania State University

Heterosturctures containing AlSb and InAs are attractive for next generation high-speed, low-power transistors and circuits because they provide a channel with a high electron mobility and high peak electron velocity at low electric field. For high electron mobility transistors fabricated from these heterostructures, thermally stable gate metallizations with modest leakage currents are required. In this study, TiW/Ti/Pt/Au, Al/Ti/Pt/Au, Ir/Ti/Pt/Au, Al, Ti/Au, and W/Au gate metallizations were examined. The thicknesses of the metals were varied, as were the deposition conditions, including whether electron-beam evaporation, thermal evaporation, or DC magnetron sputtering were used. Each sample was aged at temperatures from 200–350°C for 1 h or longer. Both Al-based and TiW-based contacts provided excellent thermal stability at 250°C. The role of the metal deposition conditions on otherwise identical metallizations is highlighted through discussion of the Al/Ti/Pt/Au contact. Based on Auger electron spectroscopy (AES) depth profiles and cross-sectional transmission electron microscopy (TEM), no significant intermixing of the metal layers or consumption of the semiconductor is observed when gate metals are thermally stable. Identification of failure mechanisms in severely stressed metallizations is now underway using AES and TEM.

10:00 AM Break

10:20 AM

DD6, Heavily Strained InGaAsSb/AlGaAsSb Quantum Well Heterostructures for Optoelectronic Applications: *Dmitri Donetsky*[1]; Leon Shterengas[1]; Michail Kisin[1]; [1]Stony Brook University

This paper reports on progress in development of heavily-strained InGaAsSb/AlGaAsSb quantum well (QW) heterostructures for laser diodes, laser diode arrays, light emitting diodes operating at room temperatures in the wavelength range of 2.2-3.4 µm. The research effort was focused on optimization of the material composition and compressive strain in the Type-I InGaAsSb/AlGaAsSb QW heterostructures for maximum radiative efficiency. It is well known that the compressive strain significantly improves parameters of laser diodes due to increase of the differential gain obtained with balancing the density of states for electrons and holes in the quantum well. Another important benefit of the compressive strain for the InGaAsSb/AlGaAsSb heterostructures is an increase of the effective barrier height for the quantum-confined hole states. More efficient confinement of holes improves the temperature stability and output power of InGaAsSb/AlGaAsSb-based light emitters designed for operation at longer wavelengths. The QW heterostructures were grown on Te-doped GaSb substrates in the solid source molecular beam epitaxy system Veeco GEN-930. For room-temperature operation near 2.4 µm the laser diode active region contained two 12-nm-wide In0.37Ga0.63As0.1Sb0.9 QWs spaced 20 nm apart in the center of the AlGaAsSb waveguide layers with 25% Al composition. The undoped waveguide and doped cladding layers with 90% Al composition were lattice matched to GaSb. The heterostructures were processed into 100-µm-wide gain-guided lasers. Increase of the compressive strain to 1.6% resulted in the room-temperature threshold current density of 65 A/cm^2 per QW for 1 mm uncoated lasers. The rate of increase of the modal gain with current was above 200 1/cm/A. The injection efficiency in excess of 80% was determined from the external efficiency and total loss. The room-temperature CW output power exciding 1 W level was obtained at the wavelength of 2.4 µm from 2-mm-long devices mounted p-side down onto polished copper blocks. Thus, for laser structures with the compressive strain of 1.6% a two-fold decrease in the device threshold current and three-fold improvement of the rate of increase of the modal gain with current were achieved compared to the parameters reported previously for similar laser structures with the compressive strain of 1.2%. These improvements are primarily associated with increase of the differential gain and hole confinement. Calculations suggest that in InGaAsSb/AlGaAsSb QW heterostructures with the described above compositions the hole barriers are increased from 40 to 116 meV with increase of the compressive strain from 1.2 and 1.6%. This work was supported by the US Air Force under grants FA95500410372, FA955005C0043, ARO under grant DAAD 190310259 and by NYSTAR under Contract C020000.

10:40 AM Student

DD7, Arsenic-Free Long Wavelength Mid-IR Emitters on GaAs Substrate: *Yaxin Yu*[1]; Rajeev Shenoi[1]; L. Ralph Dawson[1]; Sanjay Krishna[1]; Diana Huffaker[1]; Ganesh Balakrishnan[1]; [1]University of New Mexico

High-quality mid-infrared emitters operating in the range of 2-5µm can be used in a wide range of applications including ultra-low loss communication, trace gas spectroscopy, infrared countermeasures, LADAR and remote sensing. Presently, most mid wave infrared (2-5µm) emitters are grown on GaSb substrate. However, to extend the wavelength of operation beyond 1.7µm, arsenic needs to be incorporated into the heterostructure. This has resulted in degraded device performance partly due to a deleterious loss in valence band offset. Moreover, one would prefer the growth of these devices on a cheap and mature GaAs substrate technology, thereby alleviating the effect of residual oxide on the GaSb substrate. In this abstract, we report the growth of As-free Type-I GaInSb Quantum Well mid-infrared emitters on GaAs substrates using solid-source molecular beam epitaxy (MBE). The growth commenced with a 200Å GaAs smooth layer after which the substrate temperature was lowered to around 510°C. Following that, a 1µm GaSb layer was then grown on the top to provide a virtual metamorphic substrate. This is a fundamentally different growth mode that results in low-defect GaSb bulk material in which strain energy is solely relieved by laterally-propagating misfit dislocations confined to the epi-substrate interface. The nomarski pictures indicate a very smooth GaSb surface. Using double crystal X-ray diffraction, a 60" FWHM of the GaSb peak was measured compared to the 40" FWHM for the GaAs substrate peak. This indicates the high crystalline quality of the GaSb layer. After that, a 0.5µm AlSb layer was grown and the temperature was then reduced to 475°C for the growth of AlInSb buffer layers. The AlInSb metamorphic buffer layer is composed of a 50Å period of Al0.7In0.3Sb/AlSb digital alloy (DA) superlattice. The active region consists of three 1% compressive-strained 100Å Ga0.49In0.51Sb Quantum Wells with Al0.73In0.27Sb barriers. Finally, a 125Å GaSb cap layer was grown on the top. Under the optimized growth conditions, the sample exhibits strong room temperature photoluminese(PL) at around 2.5µm under illumination from a 980nm laser diode. The nomarski pictures of the PL sample show a very clear crosshatching pattern, which confirmed a high quality sample surface. We are presently investigating electrically injected devices and the results from this study will also be discussed in the presentation.

11:00 AM

DD8, Extended Wavelength Lattice-Mismatched InP-Based Avalanche Photodiodes: *Christine Wang*[1]; Erik Duerr[1]; Joseph Donnelly[1]; David Chapman[1]; [1]Massachusetts Institute of Technology, Lincoln Laboratory

Geiger-mode avalanche photodiodes (GM APDs) are of interest for a variety of low-light level applications, including three-dimensional laser radars and photon-counting optical communications. The state-of-the art for short wave infrared region (SWIR) detection utilizes lattice-matched (LM)InP-based materials, which have detection limitation to 1.6 µm. As there is good atmospheric transmission between 1.9 and 2.5 µm, GM APDs with sensitivity in this region would open up new application areas for covert detection and biological and chemical sensing. Several approaches exist for GM APDs with detection capability between 1.6 and 2.5 µm. The conventional approach is the use of LM GaSb-based alloys, with GaInAsSb and AlGaAsSb as the absorbing and multiplier layers, respectively. Alternatively, LM GaInAs/GaAsSb superlattice absorber layers can be used with InP multiplier layer.[1] Another approach, which is the focus of this work, is alloys grown lattice-mismatched (LMM) to InP substrates. InPAs is grown as both the buffer and multiplier layer. A GaInAs absorber layer grown lattice-matched to the InPAs multiplier layer allows detection to be reasonably extended beyond 1.6 µm to 2.5 µm. LMM InPAs epilayers were grown on (100) 2° toward [110] semi-insulating InP substrates by organometallic vapor phase epitaxy at a temperature of 580°C. Trimethylindium, tertiarybutyl phosphine, and tertiarybutyl arsine were used as precursors with Si2H6 and disopropyltellurim as n-type dopants and diethylzinc as the p-type dopant. The growth scheme used for the step-graded InPAs buffer layer was optimized based on surface morphology, luminescence efficiency, and minimized broadening in x-ray diffraction.

The InPAs composition was step-graded in increments of 5% over a layer thickness of 0.5 µm to a final InPAs composition of 25%, which corresponds to 1.9 µm detection for GaInAs matched to InPAs. A step-flow growth mode was preserved throughout the growth, and the full-width at half-maximum of x-ray diffraction curves was as low as 131 arc s. APD test devices were fabricated and tested. Dark count rates ranged from 50 to 150 kHz at 5V over-bias for 30-µm-diam devices tested at 100 K. These values are comparable to GaSb-based p-i-n diodes operated in Geiger mode. Reset times of 0.1 ms were sufficient to prevent after-pulsing. These times are approximately three orders of magnitude lower than GaSb-based APDs.[2] Thus, LMM InPAs/InP is a very viable materials system for extended wavelength InP-based APDs. This paper will discuss the details of design, growth, characterization, and performance of LMM InPAs/InP GM APD devices. [1] R. Sidhu, L. Zhang, N. Tan, N. Duan, J. C. Campbell, A. L. Holmes Jr., C.-F. Hsu, and M. A. Itzler, Vol. 42, pp. 71-72, 2006. [2] E. Duerr,M.J. Manfra, M.A. Diagne, R.J. Bailey, J.P. Donnelly, M.K. Connors and G.W. Turner, to be published, CLEO 2007, Baltimore, MD.

11:20 AM

DD9, 1.65 µm III-Sb Quantum Well Lasers on GaAs Substrates Enabled by Interfacial Misfit Dislocation (IMF) Based Nucleation: *Ganesh Balakrishnan*[1]; Manish Mehta[1]; Maya Kutty[1]; Shenghong Huang[1]; Anitha Jallipalli[1]; L. Ralph Dawson[1]; Diana Huffaker[1]; [1]University of New Mexico

The GaSb material system is a proven platform for type-I diode lasers operating between 1.6 µm and 3.0 µm. Most of this work has been demonstrated on native GaSb substrates. In this presentation, we detail techniques for achieving high quality III-Sb devices on GaAs rather than on GaSb substrates. The growth of high-quality III-Sb layers on GaAs substrates is achieved through the use of interfacial array of misfit (IMF) dislocations that relieve the strain from the 7.78% lattice mismatch at the GaSb/GaAs heterojunction. The IMF array is comprised of pure 90° dislocations that run along the (110) and the (1-10) directions, formed by Sb atoms periodically skipping every 14th underlying Ga atom. Based on this interfacial technology, a 1.65 µm edge-emitting GaSb/AlGaSb quantum well laser on GaAs is demonstrated. The device operates in the pulsed current mode at room temperature, produces 15 mW peak power at -10°C, and has high characteristic temperature (To=83K @ 300K) for an Sb-based active region. We also demonstrate a new class of vertical-cavity light emitting diodes (VLEDs) operating at 1.65µm that encapsulate a III-Sb active region in III-As matrix using two sets of IMFs. One set involves growth of GaSb on GaAs and the second involves the growth of GaAs on GaSb. The IMF formation is shown to be strongly associated with a (2 x 8)-Sb reconstruction on the GaAs substrate. This association is verified using cross-section transmission electron microscopy (TEM). The IMF array reduces the defect density in the GaSb layer to below 10^5 defects/cm^2 as verified through plane view TEM. The (2 x 8)-Sb surface reconstruction is optimized through reflection high-energy electron diffraction (RHEED), high resolution X-ray diffraction (HR-XRD), photo-luminescence (PL) and TEM studies. The laser and VLED characterization data including spectral data, I-V and L-I curves will also be presented.

11:40 AM

DD10, Fabrication and Characterization of a Photonic Crystal DFB Interband Cascade Laser Operating at 3.3 µm: Chul Kim[1]; Mijin Kim[1]; William Bewley[1]; Chadwick Canedy[1]; *Jill Nolde*[1]; Diane Larrabee[1]; J. Lindle[1]; Igor Vurgaftman[1]; Jerry Meyer[1]; [1]Naval Research Laboratory

Midwave-infrared (mid-IR) lasers that combine high continuous-wave (cw) output power with emission into a single spectral mode and/or near-diffraction-limited beam quality are needed for a variety of military and commercial applications. These include remote chemical sensing, free-space communications, and IR countermeasures. In the photonic-crystal distributed feedback (PCDFB) approach, diffraction by a two-dimensional grating provides optical coherence across a wide gain stripe. While we previously demonstrated optically-pumped PCDFB devices, here we report the first electrically-pumped mid-IR PCDFB lasers with type-II "W" interband cascade active regions. The 10-stage interband cascade active region, which was surrounded by InAs/AlSb superlattice n-cladding regions of thicknesses 0.46 µm (top) and 4.06 µm (bottom), was grown by molecular beam epitaxy on a GaSb substrate. The 2D grating was written by electron beam lithography, followed by e-beam deposition of 100 nm of Ge and subsequent lift-off. The resulting pattern was a 1st-order rectangular PCDFB grating with short-axis period 526 nm at 90% duty cycle, and long-axis period 1.446 µm with 33% duty cycle. A chemical etch was used to form ridges that were oriented 20° off the facet normal direction. SiO_2 was next sputtered on top of the ridge, and contact vias of width 5 µm and period 20 µm were opened parallel to the sidewall. The top contact metallization was Ag/Ti/Pt/Au. Finally the devices were thinned to 170 µm, metallized on the back with Ag/Cr/Sn/Pt/Au, annealed at 300°C for 1 minute, cleaved to form laser cavities, and mounted epitaxial side up. Since the PCDFB lasing mode relies only on the grating for feedback, both facets were anti-reflection-coated to suppress parasitic Fabry-Pérot modes. A device with ridge width 270 µm and cavity length 0.75 mm exhibited PCDFB lasing at a wavelength of 3.3 µm. The threshold current had its minimum of 130 A/cm^2 at $T \approx 95$ K, where the gain peak was in resonance with the grating. At T = 78 K the maximum cw output power was 43 mW. At 90 K and high currents the spectrum narrowed to a single peak with an instrument-limited linewidth ≈ 1 Å and SMSR ≈ 20 dB. The lasing mode shifted by 5.2 nm over the temperature range 78–100K, which corresponds to a tuning rate of 2.4 Å/K. At 100K, the lasing wavelength tuned over a similar range (4.8 nm) by varying the injection current. In the far-field, 80% of the power is emitted into a central lobe whose angular divergence of 0.9° is diffraction-limited to within experimental uncertainty.

Session EE:
Epitaxy for Devices

Friday AM — Room: 138
June 22, 2007 — Location: DeBartolo Hall

Session Chair: Archie Holmes, University of Virginia

8:20 AM Student

EE1, MBE Grown Multifunctional Heterostructures-Combining Ferromagnets with Insulators and Ferroelectrics: *Swedesh Srivastava*[1]; Christoph Adelmann[1]; Charles Brook[2]; Michael Biegalski[2]; Darrell Schlom[2]; Charles Ahn[3]; Chengtao Yu[4]; Michael Pechan[4]; Chris Palmstrom[1]; [1]University of Minnesota; [2]Pennsylvania State University; [3]Yale University; [4]Miami University

The coupling of the magnetic property of a ferromagnetic film with the piezoelectric property of a piezoelectric material such as $BaTiO_3$ via strain can be used for controlling magnetic properties with an electric field and vice versa. Such multifunctional heterostructures can lead to multiferroic behavior. The differences in crystal structure and chemical bonding of these dissimilar materials make heteroepitaxial growth challenging. In order to determine effects of lattice mismatch and interfacial bonding, Fe and the Heusler alloy Co_2MnGe were grown by solid source MBE on $SrTiO_3$ (001), $BaTiO_3$ (001), MgO (001) and GaAs(001) substrates. Although epitaxial Fe has been grown on $SrTiO_3$, [1,2] detailed studies of the growth temperature effects on the morphology and properties of Fe films are lacking. Prior to MBE growth, the bulk oxide substrates were prepared by ex-situ annealing in flowing O_2. Fe grew with a 45° in-plane rotation on the oxide surfaces resulting in a lattice mismatch of 3.8% and 1.5% for growth on $SrTiO_3$(001) and $BaTiO_3$(001), respectively. For growth at substrate temperatures below 300°C the Fe grows epitaxially with a (001) orientation as observed by RHEED and X-ray diffraction. Whereas the Fe film grown on $BaTiO_3$ surface at 350°C had domains of two orientations (002) and (211) Fe which was also substantiated by the domain structures observed in the AFM images of these surfaces. X-Ray diffraction measurements showed that both the substrate quality and the growth temperature had dramatic effects on the quality of the Fe film. These films show in-plane 4-fold magnetic anisotropy with the easy direction being Fe [100] as observed in the FMR. Co_2MnGe was also found to grow with a 45° in-plane rotation on the oxide surfaces resulting in a lattice mismatch of 3.9%, -1.7%, and -3.7% for growth on $SrTiO_3$(001), $BaTiO_3$(001) and MgO(001), respectively. Surprisingly, the x-ray diffraction data for Co_2MnGe grown below 450°C epitaxially on $SrTiO_3$ and MgO suggest that Co_2MnGe grows in a new relaxed tetragonal phase (a = 5.72Å, c = 5.81 Å). Co_2MnGe films grown at higher temperatures grow in the expected cubic structure. Thinner films, 50Å films were found to have similar trend in the lattice parameter suggesting that the films are relaxing even before a thickness of 50Å .X-ray diffraction also suggests that the higher the growth temperature the better is the crystal quality. The low temperature tetragonal phase, in contrast with the high temperature cubic phase, has induced perpendicular magnetocrystalline anisotropy. These results are different from Co_2MnGe growth on GaAs [3], where Co_2MnGe grows pseudomorphically on GaAs(001) despite the 1.6% lattice mismatch. This presentation will emphasize the influence of growth conditions and lattice mismatch on the structural and magnetic properties of ferromagnet/oxide heterostructures.

8:40 AM Student
EE2, MOCVD Growth of InAlGaAs-InP Light-Emitting Transistors Operating at ~1.55 μm: X. B. Zhang[1]; F. Dixon[2]; *Y. Huang*[1]; J. H. Ryou[1]; M. Feng[2]; N. Holonyak[2]; Russell Dupuis[1]; [1]Georgia Institute of Technology; [2]University of Illinois at Urbana-Champaign

The base current plays a key role in the traditional three-port transistor operation. A fraction of the base current is usually lost due to recombination but optimization of this effect can yield substantial radiative recombination in the base of direct band-gap semiconductor heterojunction bipolar transistors (HBTs). By tailoring the design of the base, that is, intentionally incorporating quantum wells (QWs) in the base region, radiative recombination in the base region can be effectively increased, which has resulted in the demonstration of three-port heterojunction bipolar light-emitting transistors (HBLETs or simple LETs). The LETs combine the functionality of transistors (amplifying an electrical input signal), and that of light-emitting devices (converting an electrical input signal into an optical signal), and thus has promising applications in processing both the electrical and optical signals. Since the demonstration of the first LETs, great achievements have been made in this field. Room-temperature operation of transistor-lasers (TL), based upon LET structures, has been demonstrated and its capability of TLs for microwave modulation have been investigated. The TLs demonstrated to date have been based on AlGaAs/GaAs with strained InGaAs QW structures and hence the emission of the light is limited in the near-infrared (λ~980 nm) wavelength region. For optical communication applications, the operating wavelength should be extended to either ~1.3 or ~1.55 μm. This work, we have developed an LET structure based on the InAlGaAs-InP material system with emission at ~1.55 μm for optical communication and high-speed signal amplification applications. InAlGaAs-InGaAs QW-InP *NpN* LET structures with emission wavelength around 1.6 μm were grown on (001) InP substrates. Atomic-force microscopy, X-ray diffraction, photoluminescence, Hall effect, and secondary ion mass spectroscopy were used to optimize the surface, the structural, the optical properties, and the doping profile of the epitaxial layers. Three different epitaxial structures in the base/active region were grown and fabricated into devices: 20 nm SQW, two 15nm-QWs, and three 15nm-QWs. As the number of QWs in the base increases, the current gain of the transistor decreases. This is attributed to more efficient minority carrier collection into the QWs, followed by radiative recombination, as the QW portion of the base region increases. The electroluminescence (EL) optical outputs of LETs consisting of three different active/base regions are also compared. EL from the InGaAs QWs of the LETs emits the light with peak intensity at λ~1.65 μm. The light output is independent of collector-to-emitter voltage, V_{ce}, while it increases as the base current, I_b, increases for all of the structures. Also, light output increases as the QW active region volume increases. The highest optical output was achieved from 3QW devices and this supports the proposed mechanism of current gain-light output relationship in terms of minority carrier collection followed by radiative recombination.

9:00 AM
EE3, The Development of InGaAs Thermophotovoltaic Cells on InP Using Strain-Relaxed InPAs Buffers: *J. G. Cederberg*[1]; J. D. Blaich[1]; G. R. Girard[1]; M. S. Hightower[1]; S. R. Lee[1]; D. P. Nelson[1]; C. S. Murray[2]; [1]Sandia National Laboratories; [2]General Atomics

Thermophotovoltaic (TPV) energy conversion is being developed for cogeneration and remote power generation applications. Our design is targeting monolithic interconnects for serial cell arrangements. A strain-relaxed InPAs buffer grown on a semi-insulating InP substrate serves as a template for unstrained InGaAs TPV cell growth. Three observations showing the effect materials problems have on device performance will be discussed, and our most recent results on TPV cells will be presented. The morphology of InPAs is modified by heavy Te doping (5E18 cm-3). Undoped and Si-doped InPAs buffers display an RMS roughness of 10 to 20 nm, while Te-doped buffers consistently show an RMS roughness under 5 nm. We interpret this observation as evidence that Te promotes adatom diffusion on the surface, which limits faceting of the cross-hatch pattern induced by misfit dislocations. Te-doping also reduces the incorporation efficiency of As into InPAs suggesting a chemical effect on the growth. In contrast, Si- and Zn-doped InPAs show no impact on As incorporation. While Te-doping improves the InPAs morphology, it displays a problematic memory effect. Long after other dopants would have desorbed or incorporated into the crystal, Te maintains a high background concentration, which compensates the p-type doping needed for tunnel junctions. We observed the lack of a tunnel junction between the n-type InPAs buffer and the p-type base of the TPV cell as a positive photocurrent under low illumination. At higher junction illumination, sufficient photocarriers contribute to the conduction, and the photocurrent becomes negative. By interrupting growth and purging the interface between the n- and p-layers of the tunnel junction for long times (up to 5 minutes) under a high arsine partial pressure (1 torr), the Te on the surface is reduced allowing a functional tunnel junction to be grown.The reverse breakdown voltage of a TPV cell is very sensitive to surface defects that form during the growth of the InGaAs cell. The origin of these defects is open to speculation, but at sufficient densities these defects act as a parallel conduction path through the cell and result in early reverse breakdown. Careful attention to the pre-growth procedure allowed us to eliminate defect shunting of the junction. The TPV cells under development are designed for operation at a wavelength of 2.0 microns and have achieved an external quantum efficiency of 60% at this wavelength. The low EQE suggests that our devices are limited by the thickness of the InGaAs absorber. Even with this deficiency, we have produced TPV cells that generate more than 345 mV/junction with fill-factors of 70%. 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.

9:20 AM
EE4, Enhanced Mobility Delta-Doped p-Channel AlInAs/GaInAs HFETs on InP: *Changhyun Yi*[1]; Michael Morse[1]; Inho Yoon[1]; April Brown[1]; [1]Duke University

For digital applications, the implementation of complementary circuits achieved by combining 2DEG (dimensional electron gas) and 2DHG (dimensional hole gas) HFETs (heterostructure field effect transistors) is attractive due to the prospect of low power consumption and enhanced threshold-voltage uniformity, and large noise margin. Hole mobility enhancement is a critical barrier to realizing this technology. To date, most of the reported III-V p-channel HFET structures utilize AlGaAs/GaInAs HFETs grown on GaAs. We show that strained p-channel HFET structures with delta-doping yield improved mobility for the GaInAs/AlInAs on InP heterojunction system. To do so, the InAs composition of the $Ga_xIn_{1-x}As$ channel layer was varied from 53% to 73%. 2DHG concentrations and hole mobilities for HFETs with different channel thicknesses were grown using solid source MBE. The use of a delta-doping scheme enables a relatively low doping level in the AlInAs donor layer for the gate barrier, and therefore increases, with respect to a distributed doped structure, the device breakdown voltage without sacrificing the channel sheet charge density. The Be-doping levels were varied to determine the acceptor density impact on 2DHG densities and conductivities. The basic structure consists of a 250nm AlInAs buffer, followed by a $Ga_xIn_{1-x}As$ channel. After a 5nm AlInAs spacer is grown, the growth is interrupted for the deposition of the delta-doped Be-plane, and then resumed for a 20 nm AlInAs Schottky barrier layer and a 10nm GaInAs contact layer doped at p=8E18cm^{-3}. To measure the electrical transport properties of the 2DHG, the contact layer was etched away in order to remove possible parallel conduction during Hall measurement. The highest Hall mobility and density for the 2DHG in a 10nm strained Ga0.27In0.73As channel was measured to be 298 cm^{-2}/Vs and 0.8E12 cm^{-2} at 300 K, while that of the lattice matched Ga0.47In0.53As channel was 106 cm^{-2}/Vs and 1.3E12 cm^{-2}. The enhanced hole mobility observed with the strained channel is expected to lead to improved device performance. However, when the channel thickness is greater than 15nm (μh=149 cm^{-2}/Vs,2DHG=1.01E12 cm^{-2}), the hole mobility decreases by approximately 10 ~ 15% due to increasing numbers of residual electrons in the channel with both increasing In channel concentration and channel thickness. The 2DHG concentration decreases with these factors due to compensation. When the channel thickness is greater than 20nm, the hole mobility decreases an additional 25 ~ 30% as compared to the structure of 10nm channel. Therefore, there is a trade off in increasing the channel In composition to achieve higher mobility, but at the cost of higher scattering and 2DHG compensation.

9:40 AM Student

EE5, Stress in Nano-Scale Patterned Strained Silicon/Strained Germanium/Strained Silicon Heterostructures on Insulator: *Pouya Hashemi*[1]; Leonardo Gomez[1]; Michael Canonico[2]; Judy Hoyt[1]; [1]Massachusetts Institute of Technology, Microsystems Technology Laboratories; [2]Physical Analysis Laboratory Arizona (PALAZ), Freescale Semiconductor, Inc.

Strained Si/SiGe(Ge)/Si heterostructure on insulator (HOI) MOSFETs are promising structures for future generations of CMOS technology due to their enhanced electron and hole mobility. However, when these substrates are patterned into nano-scale mesas and fins, some changes in the stress profile are expected which can either degrade or enhance the mobility of the devices. In this work, we report these stress changes for different geometries to study the relaxation of the individual layers as well as to further optimize the channel stress in order to achieve higher device performance. The epitaxially grown strained Si/strained Ge HOI substrates used in this experiment were fabricated utilizing a bond and etch-back method. The strained Si cap thickness was varied by thinning the Si cap layer by wet chemical oxidation and subsequent oxide removal. The purity of the Ge layer and the amount of relaxation was characterized by high-resolution x-ray diffraction (XRD) and it was found that due to silicon inter-diffusion, the Ge layer has a composition of ~95 atomic % with no significant relaxation. Ultra-thin strained HOI substrates were then successfully patterned into long bars and device mesas with different aspect ratios. Scanning electron beam lithography with HSQ as a negative tone resist was used to create nano-scale widths ranging from 30nm to 300nm. The density of these features is key to achieving a measurable Raman signal. The pattern transfer was performed in a RIE system stopping at the buried oxide interface. To analyze the stress profile in the patterned features, UV Micro-Raman spectroscopy was utilized with 325nm He-Cd and 364nm Ar-Ion laser lines for Ge-Ge and Si-Si bonds, respectively. Excitation by 325nm laser line can enhance the Ge signal by a factor of ~1.8 over the 364nm line. The Raman measurements on the long bar structures reveal an increase in relaxation of the Ge layer when the feature width is reduced from 300nm to 30nm. This relaxation trend was also seen in the Si cap layer at various cap thicknesses. For the patterned mesas with various aspect ratios (from 3:1 to 1:1), a general trend of relaxation with decreasing aspect ratio was observed. The 100nm square-shape mesas show nearly 33% relaxation (assuming isotropic biaxial strain). This result indicates that a large amount of strain can be preserved in patterned regions suitable for fabrication of HOI MOSFETs. In addition, finite element stress simulations demonstrate that the stress component along the bars is almost maintained while the in-plane component tends to relax in the narrow direction of the bars. By further engineering the strained layer thicknesses and utilizing this pattern-induced relaxation method, it should be possible to enhance the mobility of devices compared to biaxially strained substrates.

10:00 AM Break

Session FF:
III-Nitride: Pseudo-Substrates

Friday AM
June 22, 2007

Room: 138
Location: DeBartolo Hall

Session Chair: Randall Feenstra, Carnegie Mellon University

10:20 AM

FF1, Fabrication of 3-Inch Freestanding GaN Substrates by Hydride Vapor Phase Epitaxy with Void-Assisted Separation: *Yuichi Oshima*[1]; Takehiro Yoshida[1]; Takeshi Eri[1]; Kazutoshi Watanabe[1]; Masatomo Shibata[1]; Tomoyoshi Mishima[1]; [1]Hitachi-Cable, Ltd.

Recently, freestanding GaN substrates with a diameter up to 2 inches have been put to practical use. Due to the increase in output power of nitride devices, size of these devices is likely to increase in the future. Therefore, GaN substrates with a larger diameter will be needed for cost effective use. However, few reports exist on fabrication of GaN substrates with a diameter greater than 2 inches. Therefore, manufacture of 3-inch GaN substrates was attempted. Hydride vapor phase epitaxy (HVPE[1]) and void-assisted separation (VAS[2]) were utilized for fabrication of freestanding GaN substrates. In the VAS method, a thick GaN layer, grown through HVPE, is separated from the base substrate owing to the numerous voids generated around the thin TiN layer inserted between the thick GaN layer and the base substrate. As a result, a large-diameter GaN substrate can easily be obtained. Fabrication by VAS of 2-inch GaN substrates with excellent reproducibility has already been reported.[2] This study used 3.4-inch-diameter (0001) sapphire as base substrate. HVPE growth was performed on a 3.2-inch-diameter area of the base substrate. Thickness of the thick GaN layer was approximately 600 µm. After HVPE growth, the thick GaN layer was spontaneously separated from the base substrate due to thermal stress. As a result, a GaN substrate with a diameter of approximately 3.2 inches was obtained. The surface was mirror-like. No cracks were generated during repetition of the same process several times. These findings suggest that reproducibility of this process is very high. Peripheries of the as-grown GaN substrates were grinded, and 3-inch GaN substrates obtained. Dislocation density, determined through cathode luminescence measurement, was of the order of 10^6 cm^{-2}. X-ray rocking curve measurements showed that full widths at half maximum (FWHM) of GaN (0002) and (10-10) peaks were narrow, namely, 56 and 88 arcsec, respectively. Crystal quality was very good, and further improvement would be possible by optimizing growth conditions. High-quality freestanding GaN substrates with a diameter greater than 3 inches were able to be produced. There was no additional difficulty in the separation process compared to 2-inch substrates. Therefore, further enlargement of the diameter is likely possible using the VAS method. This result greatly contributes to the potential for high-performance, low-cost nitride devices. [1]H. P. Marusuka and J. J. Tietjen, Appl. Phys. Lett. 15 (1969) 327; [2]Y. Oshima, T. Eri, M. Shibata, H. Sunakawa, K. Kobayashi, T. Ichihashi and A. Usui: Jpn. J. Appl. Phys. 42 (2003) L1.

10:40 AM

FF2, Mechanisms of AlGaN Growth with Reduced Dislocation Density on Patterned GaN: *David Follstaedt*[1]; Andrew Allerman[1]; Joseph Michael[1]; Stephen Lee[1]; Nancy Missert[1]; Mary Crawford[1]; [1]Sandia National Laboratories

To produce optical devices emitting in the ultraviolet, thick (>1 µm) AlGaN alloy layers are needed with low dislocation densities. However, high densities of threading dislocations and cracks are generated in AlGaN films grown on GaN. To overcome these problems, GaN layers have been patterned with trenches; subsequent AlGaN overgrowth fills the trenches and turns dislocations to produce an alloy with low dislocation density over the trenches (see Iwaya et al., Proc. SPIE vol. 5738, p. 210 (2005); Bell et al., Appl. Phys. Lett. 85, 3417 (2004)). We have extended the aspect ratios and compositions of such structures and used cross-sectional TEM to examine Al24Ga76N grown on GaN etched with trenches ~1 µm deep and up to 10 µm wide, sufficient to allow emitting devices to be placed in low dislocation areas at the top surface. Focused ion beam milling of the TEM specimen was done using an FEI Helios dual-beam instrument that milled the cross-sectional slice with a 30 kV Ga beam and then "trimmed" it with energies down to 2 kV to reduce surface damage. A thin (~30 nm) AlN interlayer was grown first on the patterned GaN followed by MOCVD growth of AlGaN. Several growth morphologies were observed over the trench, and their growth modes can be deduced from the direction of threading dislocations. AlGaN grows vertically out of the flat trench bottom and laterally off the sidewalls. The lateral growth ends at the top of the trench. Growth proceeds instead from the top edge of the trench at an angle of ~40° from vertical in ~2 µm-wide section. This growth proceeds from both sides, inclined over the center of the trench where vertical growth continues. The angled material has lower dislocation density and overgrows the central, vertical growth with its high density. At the interface between these two sections, the vertical dislocations in the center are turned and crowded together; detailed examination shows that they frequently connect with other threads to form "hairpins" and propagate no further. Growth of this specimen was halted twice to inspect with SEM; the growth surfaces at these times can be detected in TEM images and confirm these growth modes inferred using dislocations. The two angled growths meet above the center of the trench, and a narrow tangle of dislocations continues to the surface 8 – 10 µm above the GaN. The material between this tangle and the edge of the trench has very low dislocation density at the surface; we estimate ~10^8/cm^2, which may be suitable for UV lasers. 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.

11:00 AM Student

FF3, Microstructural Evolution in the Initial Growth Stage of m-Plane GaN on m-Plane SiC with a High-Temperature Grown AlN Buffer: *Qian Sun*[1]; Soon–Yong Kwon[1]; Zaiyuan Ren[1]; Jung Han[1]; Takeyoshi Onuma[2]; Shigefusa F. Chichibu[2]; [1]Yale University; [2]Tohoku University

Heteroepitaxial growth of nonpolar III-nitride semiconductors has encountered at least two major issues. First, the density of extended defects in nonpolar GaN films, including threading dislocations and stacking faults, appears to be not only much higher than that in c-plane epitaxial GaN but also anisotropic. At the same time, the surface of nonpolar III-nitrides (a- and m-planes) frequently exhibits striation morphology accompanied by high roughness. Relatively little has been reported regarding the microstructural evolution of m-plane GaN, especially in the initial growth stage, which profoundly impacts the surface morphology and crystalline quality of m-plane GaN film. In this paper, we present a study of m-plane GaN nucleation and subsequent island coalescence on m-plane 6H-SiC substrate; an attempt will be made to correlate observations such as surface morphology, anisotropic mosaic microstructure, and luminescent efficiency. A high-temperature AlN buffer layer with a nominal thickness of 220 nm (determined by in situ reflectance) was grown on chemically and thermally cleaned m-plane SiC substrates with a V/III ratio of 3500. The AlN buffer layer shows a smooth morphology under AFM and replicates some of the polishing scratches on the as-received SiC surface. These random straight grooves with a depth of around 4 nm work as facilitated nucleation sites for m-plane GaN, which results in an non-uniform nucleation both in location and time. As the growth proceeds, those nuclei develop into discrete faceted islands with a great variety of size and height. Under normal growth conditions, the faceted islands are enclosed by three {10-11} and three {10-10} planes, as well as the nitrogen-terminated (000-2) plane. When the faceted islands approach each other along c-axis, a triangular, concave gap is formed by (10-11) and (000-2) planes. Subsequent coalescence proceeds to fill the triangular gap into a curved surface, creating surface undulation along c-axis between the coalesced/filled and original regions. High resolution x-ray diffraction (XRD) on a series of m-plane GaN samples with controlled interruptions at different stages of coalescence reveals a transition of XRD features from a single peak to broadened and even split peaks when the x-ray plane is perpendicular to the in-plane a-axis. This observation indicates that the coalescence region is mis-oriented with respect to the islands and has more structural defects, which has been confirmed by micro-CL monochromatic imaging measurement. It is speculated that there may be formation of basal plane stacking faults and generation of threading dislocations during the asymmetric coalescence between (10-11) and (000-2) planes.

11:20 AM Student

FF4, Growth and Characterizations of Auto-Roughened LED Grown on Wet-Etched Stripe-Patterned Sapphire Substrate: *Kar Wei Ng*[1]; Jung Min Hwang[2]; Kei May Lau[1]; [1]Hong Kong University of Science and Technology; [2]National Tsing-Hua University

Use of Patterned Sapphire Substrate (PSS) for Light Emitting Diode (LED) growth has been proven to be effective in enhancing light output power (LOP). Chemical wet etching is a promising technique for preparing PSS, without the need of expensive ICP. The characteristic inclined crystallographic facets resulted from wet-etching are believed to facilitate superior light extraction efficiency. Recently, much work has been done to study the growth of LED on PSS with dot-patterns. However, very few reports on the fabrication of LED grown on grooved substrates produced by wet-etching techniques can be found. In this work, LED was grown on a stripe-patterned substrate by MOCVD. The '_/-shaped' grooves were wet-etched along $<1\text{-}100>_{sapphire}$. The groove width, platform width and groove depth were 3µm, 3µm and 0.8 µm respectively. Footprint-like patterns aligning along $<1\text{-}100>_{sapphire}$ were found on the as-grown LED surface. The 'footprints' were discovered to be directly above the inclined sidewalls of the grooves, suggesting that the presence of inclined sidewalls was the cause for the auto-roughened surface. Transmission Electron Microscopy (TEM) was used to trace the origin of the footprints. It was found that GaN initiated on the inclined sidewalls formed 'tumor' like structures with poor crystal quality. The 'tumors' had a crystal orientation different from the GaN grown on $(0002)_{sapphire}$. Moreover, the tumor seemed to form a rough grain boundary with normal GaN, seeding dislocation bundles in the subsequent GaN growth above the inclined sidewall. We believed that these dislocation bundles slowed down GaN growth above the inclined sidewall and resulted in the formation of 'footprints', or uneven surface morphology. Using 3D Time-of-flight Secondary Ion Mass Spectroscopy (Tof-SIMS), the regions inside and outside the footprints were found to have the same Mg and In profiles, implying that the same LED structure existed in both regions. This confirmed that the formation of footprints was due to very slight growth rate differences. Significant dislocation bending was found in the grooves, as observed in TEM micrographs. This symbolized a reduction in dislocation density and thus an improved crystal quality. The grown wafer was fabricated into 300×300 µm^2 devices using standard photolithographic processes. LEDs on PSS were found to have larger reverse leakage currents than standard ones. This might be attributed to the uneven growth started from the sidewalls. In spite of this, LEDs on PSS showed nearly 30% enhancements in LOP resulting from enhanced internal quantum efficiency and better extraction efficiency through the auto-roughened surface. This shows that wet-etched stripe patterning is potentially effective in improving the wallplug efficiency of LED. The dimensions of the stripes and growth conditions of the GaN buffer have to be further optimized so as to eliminate or to reduce the dislocations caused by the sidewall growth.

11:40 AM

FF5, Low Leakage Current Schottky Diodes Fabricated from Low Defect Density MOCVD GaN Grown by Pendeo - Epitaxy: *Michael Derenge*[1]; Tsvetanka Zheleva[1]; Pankaj Shah[1]; Daniel Ewing[1]; Kenneth Jones[1]; Unchul Lee[1]; David Stepp[1]; David Benson[2]; Jay Molstad[1]; [1]U.S. Army Research Laboratory; [2]Communications and Electronics Command, Research and Development Center, Night Vision and Electronic Sensors Directorate

Electronic devices, such as HEMTs and Schottky diodes fabricated on hetero-epitaxial GaN grown on SiC, sapphire and other substrates show great potential for high-temperature, high-frequency and high-power applications. However, the high density of defects, in the order of 10^9 cm^{-2}, limit the lifetime and power potential of the devices. It is known that selective growth techniques, such as lateral epitaxial overgrowth (LEO) and pendeo-epitaxy (PE) reduce the threading dislocation density in MOCVD grown GaN by up to 3 orders of magnitude. The MOCVD process was optimized for the growth of low defect density PE-GaN on sapphire by varying the growth temperature, ammonia-to-trimethylgallium (TMG) or V:III ratio, the chamber pressure, and column-to-trench width geometry. Further, we designed and fabricated test device structures, such as Schottky diodes, to utilize the low defect density regions of PE-GaN material, and to compare their performance with the performance of Schottky diodes fabricated on conventional (non-pendeo) GaN material having a high density of structural defects. The morphology, structure and electrical properties of the PE-GaN material were characterized via scanning electron microscopy (SEM), atomic force microscopy (AFM), etch-pit density (EPD) measurements, transmission electron microscopy (TEM), cathodoluminescence (CL), and I-V and C-V measurements. Consistently the PE-GaN material revealed superior structural characteristics. The AFM RMS surface roughness is as low as 0.2 nm, and EPD is less than 10^6 cm^{-2}. CL measurements in plan view and cross sections of the material show consistently that the near band edge (NBE)intensity from the low defect density pendeo-regions is more than one order of magnitude higher compared to the seed/column regions having larger dislocation densities. Plan view CL indicates that diodes with increased reverse leakage currents correlate with the seed regions of high defect density. Electrical characteristics, such as barrier height, ideality factor, and carrier concentration were determined for Schottky diodes fabricated on the PE-GaN and conventional GaN regions. The leakage current of the diodes fabricated on the PE-GaN regions is more than one order of magnitude lower compared to that of diodes fabricated on non-pendeo material. The ideality factors for the Schottky diodes fabricated on the PE-GaN regions are 1.39 compared to 1.66 for the diodes processed on the conventional GaN regions. Potentially three terminal devices fabricated from this material will have improved capabilities for various RF applications.

Session GG:
Dilute Nitride Semiconductors

Friday AM | Room: 141
June 22, 2007 | Location: DeBartolo Hall

Session Chair: James Merz, University of Notre Dame

8:20 AM

GG1, Optical Properties and Characteristics of Dilute Nitride InN(As)Sb Quantum Well and Quantum Dot Grown by MBE for Infrared Sensors Application: *Seongsin Kim*[1]; Homan Yuen[1]; Fariba Hatami[2]; Alan Chin[3]; James Harris[1]; [1]Stanford University; [2]Humboldt-University at Berlin; [3]NASA Ames Research Center

The development of mid-infrared (MIR) and far-infrared (FIR) semiconductor laser diodes and detectors has been an on-going research topic because of the great interest in developing compact systems for high-resolution gas spectroscopy, military countermeasurement, free space communication, and low-cost medical diagnostics. Most bio-molecules and chemical and biological agents based on proteins have strong absorption and resonance fingerprints between the MIR and FIR range of 3 to 15 µm. In addition, the MIR wavelength range contains strong fundamental absorption lines of almost all gas species of interest for atmospheric measurement. Widespread and portable applications of IR lasers in this wavelength range require higher operating temperature, low power consumption, and, potentially, broad wavelength tuning to be useful for sensing these agents. Recent, newly-developed III-V dilute nitride materials have interesting physical properties which may be beneficial to enable MIR and FIR devices. The addition of small amounts of nitrogen to III-V semiconductors dramatically increases the wavelength due to the unique band interactions between nitrogen and its host material. Incorporating nitrogen into narrow-gap materials is very attractive because it can reduce the energy gap and enable emission beyond the FIR, a feat not possible with conventional III-V semiconductors. In addition, nitrogen in these materials will increase the electron effective mass, suppressing a auger recombination. We report the growth and characterization of a new dilute nitride, InNAsSb/InAs, SQW (N~1%) and InNSb quantum dots embedded on both InAs and GaAs substrate by solid source molecular beam epitaxy. Optimizing growth conditions for nitrogen incorporation has resulted in high quality InNAsSb epilayers without any structural degradation, as confirmed by high-resolution x-ray diffraction. Optical properties were investigated by temperature dependent and excitation power dependent photoluminescence. We obtained mid infrared luminescence at 4.03 µm from localized states and from the ground state transition at 4.3 µm. The electron confinement in this SQW is Type-I and not Type-II, as with InAsSb/InAs, and a band offset E^c of ~ 102meV was obtained. Nitrogen incorporation during formation of quantum dots changes surface energy barrier and causes anisotropic distribution of strain energy, results in formation of coupled multiple quantum dots in <110> orientation. We obtained mid infrared luminescence around 3.6 µm from InNSb QDs grown on InAs substrate, where it exhibits relatively low efficiencies of nitrogen incorporation compared to the quantum well structure. Detailed growth, material characterization, optical properties and modeling will be discussed.

8:40 AM Student

GG2, Composition Fluctuation and Carrier Localization in GaAs(In,Sb)N Quantum Wells: *Kai Sun*[1]; Alexander Mintairov[1]; Thomas Kosel[1]; James Merz[1]; Homan Yuen[2]; Seth Bank[2]; Mark Wistey[2]; Evan Pickett[2]; James Harris[2]; Anton Egorov[3]; Victor Ustinov[3]; Gregory Peake[4]; [1]University of Notre Dame; [2]Stanford University; [3]Ioffe Physico-Technical Institute; [4]Sandia National Laboratory

Heterostructures based on GaAs(In,Sb)N alloys having nitrogen composition of a few percent are very attractive for long wavelength emitters. It has been shown using high spatial resolution near-field photoluminescence that in these dilute nitride materials strongly localized quantum-dot-like composition fluctuations can exist, arising from nitrogen clustering. In GaAsN and GaInAsN epi-layers with In composition up to 10%, which have emission energies 1-1.2µm, such composition fluctuations have size ~15 nm, activation energy ~30 meV and density ~100 μm^{-3}, which implies their spontaneous formation (phase separation). To achieve longer emission wavelengths ~6 nm thick quantum wells (QWs) are used, having In composition up to 40%, and incorporation of antimony. In such QWs phase separation can be suppressed and very uniform material can be obtained. In the present paper we used high spatial resolution (HSR) and temperature dependent (TD) photoluminescence (PL) spectroscopy to study effects of structural uniformity on carrier localization in GaAs(In,Sb)N quantum wells emitting at 1.2-1.3µm. We studied GaAs(In, Sb)N QW samples (thickness d~6 nm) having nitrogen composition ~1.5% and different combinations of In (0 and ~35%) and Sb (2 and ~45%). As a reference we also used InAs quantum dots (QDs) structure. HSR spectra were taken using near-field optical scanning microscope or µ-PL through metallic apertures deposited directly on the samples using e-beam lithography. The spatial resolution was 200-700 nm. The structural uniformity of the QWs was monitored by HSR PL spectroscopy, transmission electron microscopy, and PL peak width. We observed quite a different TD of the PL spectra of strongly phase-separated (GaAsSbN) and structurally uniform (GaInAsSbN) QWs. GaAsSbN has the strongest PL intensity at 300 K and relatively weak TD of PL intensity, similar to that observed for InAs QDs. GaInAsSbN QW has weaker PL intensity at room temperature but extremely strong temperature dependence of PL intensity. Other dilute nitride samples show intermediate behavior between these two extreme cases. This behavior can be understood in terms of the balance between the activation of the residual non-radiative recombination centers, resulting in changing of the mean free pass of the carriers, and the suppression of carrier transport to non-radiative recombination centers due to carrier localization on the composition fluctuations. Our results reveal strong effect of composition fluctuations on emission properties of dilute nitrides. This work has been partially supported by a Subaward under NSF/DMR06-06406.

9:00 AM

GG3, Effects of Different Plasma Species on the Optical Properties of Dilute Nitrides Grown by Plasma-Assisted Molecular-Beam Epitaxy: *Michael Oye*[1]; Mark Wistey[2]; Jason Reifsnider[3]; Homan Yuen[4]; Aaron Ptak[5]; Paul May[6]; Terry Mattord[1]; Sumit Agarwal[7]; Jack Lee[1]; Sanjay Banerjee[1]; Gary Hallock[1]; James Harris[4]; Archie Holmes[8]; Seth Bank[1]; [1]University of Texas at Austin; [2]University of California, Santa Barbara; [3]Samsung Austin Semiconductor; [4]Stanford University; [5]National Renewable Energy Laboratory; [6]University of Bristol; [7]Colorado School of Mines; [8]University of Virginia

Dilute nitride semiconductors have applications in infrared optoelectronic devices and solar cells. One established growth technique for dilute nitrides is plasma-assisted molecular-beam epitaxy. The plasma source is required to activate nitrogen species for their ensuing incorporation into InGaAs. The various mechanisms associated with this incorporation have important implications on the optical properties of the material. In this work, we will present a systematic study that accounts for the effects of different ionic and non-ionic plasma species (ions, atomic N, metastable N_2*, and non-activated neutrals) on the optical properties of dilute nitride materials. To this end, a multiple quantum well structure using $Ga_{0.8}In_{0.2}N_{0.01}As_{0.99}$ quantum wells and GaAs barriers was grown in a Varian Gen-II MBE system. An Applied-Epi UniBulb RF plasma source was used to activate nitrogen species from an N_2/Ar source gas mixture. The plasma source was equipped with two parallel DC-biased deflector plates to remove ions emanating from the plasma source. Iso-nitrogen samples, which all have equivalent nitrogen composition, were grown under different plasma, ion, and growth conditions. Materials were characterized using photoluminescence (PL), where material quality was correlated by peak PL intensities. Blueshifts in the peak emission wavelengths were used to study the rapid thermal annealing-induced effects of both crystalline recovery and atomic diffusion. Both *in situ* and *ex situ* plasma diagnostic tools were used, including optical emission spectrometry and a dual-grid retarding field ion energy analyzer, respectively. The diagnostic measurements obtained from these tools were used to correlate effects of different plasma species to optical properties of dilute nitride materials. As commonly reported, the removal of ions resulted in an improvement in the optical quality; however, this work is the first to simultaneously consider the effects of different non-ionic plasma species. As such, when samples were grown without ions, there still remained a dependence on the plasma operating conditions, thus demonstrating that ions are not the only species responsible for influencing optical properties of dilute nitrides. The two non-ionic "active" nitrogen species are atomic N and metastable N_2*. Depending on the plasma operating condition, one of the active nitrogen species is more dominant. The effects of these two "active" nitrogen species are further elucidated through the peak PL emission wavelength blueshifts upon annealing, in which a predominance of atomic N leads to an increased blueshift at low annealing temperatures when compared to samples grown predominantly with metastable N_2*. In our talk, we will present additional supporting data on the important plasma species. We will then discuss our analysis of all the results geared toward obtaining high optical-quality material, which are crucial for applications such as high-efficiency lasers and photovoltaics.

9:20 AM

GG4, Characteristics of GaAsSbN/InP and GaSbN/GaSb Grown by Metalorganic Chemical Vapor Deposition: *Dapeng Xu*[1]; Juno Yuting Huang[1]; Joo Hyung Park[1]; Luke Mawst[1]; Thomas Kuech[1]; Xue Yan Song[1]; Susan Babcock[1]; [1]University of Wisconsin-Madison

Dilute-nitride materials have been studied extensively as a means to extend the emission wavelength of GaAs-based sources into the near-IR (λ~1.5μm). Little work has been reported on dilute-nitride materials and devices for emission and detection in the mid- to long–wavelength infrared spectral region (λ~3-15 μm). Due to material strain limitations, to access the LWIR spectral region dilute-nitride materials must be developed on InP or GaSb substrates. Photodetectors and emitters based on such III/V materials are highly desirable, since well established processing technology can be employed in fabrication. Dilute-nitride materials, such as GaAsSbN, with N-contents in the range of 1-2% have also been reported previously only on GaAs substrates, and can exhibit emission wavelengths >1.3 μm. However, the growth and properties of these mixed Sb/dilute-nitride alloys on InP or GaSb substrates have not been thoroughly studied to date. The GaAsSbN and GaSbN structures reported here are grown by MOCVD at a growth temperature of 520-550°C and reactor pressure of 100-200 mbar on (100) InP or GaSb substrates. Trimethylgallium (TMGa) was the group III precursor material, and AsH_3, trimethylantimony (TMSb), and U-dimethylhydrazine (U-DMHy) were the group V precursors. The solid phase material composition of GaAsSbN were determined by high-resolution x-ray diffraction (HRXRD), electron microprobe analysis (EMPA), secondary ion mass spectroscopy (SIMS), Rutherford backscattering spectroscopy (RBS), and nuclear reaction analysis (NRA) using the 14N(d,p) 15N reaction. High resolution TEM is used to evaluate the structural properties. Tensile strained GaAsSb/InP and GaAsSbN/InP SL structures are grown with the same Ga, Sb and As flow conditions. However, by introducing N, we find a significant reduction in the Sb content from 26% in the GaAsSb/InP to 13% in the GaAsSbN/InP. Based on the XRD simulation, we estimate a N-content of approximately 0.78%. LT PL (30K) measurements on the SL structures indicate that dilute nitrogen incorporation in GaAsSbN on InP extends the emission wavelength due to the nitrogen-induced bandgap bowing. In GaAsSbN/InP, the N-incorporation increases with decreasing [As]/[V] ratio and the corresponding As and Sb contents decrease. Low [As]/[V] ratio is found to produce very high N-content. However, it is likely some degree of compositional phase separation occurs and further x-ray and optical characterization studies are required to verify single phase material. Ternary alloys of GaSbN can be lattice matched to an InP substrate, provided sufficient nitrogen (~14.5%) can be incorporated. These materials have potential for very long emission or detection wavelengths (10-15 μm). Nitrogen incorporation into tensile strained GaSbN on GaSb substrates also has potential for producing narrow bandgap materials. We have undertaken preliminary studies of N incorporation into GaSbN on GaSb substrates. XRD measurements indicate N contents in the range of 0.7% have been achieved to date.

9:40 AM Student

GG5, High Sb-Content GaAsSb-GaAsN Type-II Quantum Well 'W' Structures for Long Wavelength Emission on GaAs Substrates: *Manish Rathi*[1]; Anish Khandekar[1]; Dapeng Xu[2]; Juno Huang[2]; Joo Park[2]; Luke Mawst[2]; Thomas Kuech[1]; [1]University of Wisconsin-Madison, Chemical and Biological Engineering; [2]University of Wisconsin-Madison, Electrical and Computer Engineering

GaAs-based $GaAs_{1-y}Sb_y$-$GaAs_{1-z}N_z$ type-II quantum well (QW) active regions hold potential for fabrication of 1.55 μm diode lasers. Vertical cavity surface emitting lasers (VCSELs) can be realized by growing AlGaAs-GaAs based distributed Bragg reflectors (DBRs) on these structures. Devices based on these materials should exhibit an improved temperature insensitivity due to large valence band and conduction band offsets between $GaAs_{1-y}Sb_y$ and $GaAs_{1-z}N_z$. The broad miscibility gap between $GaAs_{1-y}Sb_y$ and $GaAs_{1-z}N_z$ prevents formation of a homogeneous alloy over the entire range of desired composition under conditions of thermodynamic equilibrium. For mid-infrared range applications, the 'W' structure is widely accepted, where a hole QW is sandwiched between two electron QWs. 'W' structure provides substantial electron-hole wavefunction overlap which impacts the radiative recombination efficiency and differential gain of the device. From k•p simulations, an antimony mole fraction of 0.35 to 0.4 is desired in the $GaAs_{1-y}Sb_y$ hole well layer for strong carrier confinement and long emission wavelength. Triethyl gallium, trimethyl antimony and arsine were used here as precursors to achieve the desired high antimony content in our $GaAs_{1-y}Sb_y$ layers. Antimony incorporation in the solid film is found to be more sensitive to As/III precursor ratio in gas phase than the Sb/III precursor ratio. Preliminary photoluminescence (PL) results show emission at 1168 nm and 1204 nm from $GaAs_{1-y}Sb_y$-GaAs SL structures with antimony compositions of y = 0.35 and 0.40. Dimethyl hydrazine, triethyl gallium and arsine were used to grow the $GaAs_{1-z}N_z$ layers. Only moderate nitrogen compositions are needed of z = ~ 0.01 to 0.015 in the $GaAs_{1-z}N_z$ layers. In this case, the As/III precursor ratio was kept constant at 70 and N/III precursor ratio was varied from 70 to 240. X-ray diffraction (XRD) as well as electron probe microanalysis (EPMA) techniques are used to determine the compositions in the thin films. Abrupt interfaces between the thin layers of $GaAs_{1-y}Sb_y$ and $GaAs_{1-z}N_z$ plays an important role in device performance and have been optimized for this structure. Formation of antimony segregation layer and possible arsenic-for-antimony exchange processes lead to interfacial grading and low antimony incorporation in thin layers. In fact, a small noted discrepancy between compositions determined from XRD and EPMA can be attributed to interfacial antimony grading. Gas switching sequences and optimization to achieve abrupt interfaces will also be discussed. Samples containing 3 to 4 'W' structured $GaAs_{1-y}Sb_y$ - $GaAs_{1-z}N_z$ layers, each separated by a GaAs layer and $Al_{0.7}Ga_{0.3}$As barriers on both ends, were grown for optical and structural characterization. PL experiments show emission at 1245 nm and 1300 nm from $GaAs_{1-y}Sb_y$ / $GaAs_{1-z}N_z$ SL structures containing antimony and nitrogen composition of y ~ 0.40 and z ~ 0.005 and y ~ 0.35 and z ~ 0.013, respectively. They are in good agreement with the k.p simulation.

Notes

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2007 Electronic Materials Conference

Program-at-a-Glance

McKenna Hall	**REGISTRATION** 3:00-5:00 PM, Tuesday, June 19, 2007 7:30 AM-5:00 PM, Wednesday, June 20, 2007 7:30 AM-4:00 PM, Thursday, June 21, 2007 7:30-10:00 AM, Friday, June 22, 2007		**EXHIBITS** 9:30 AM-4:00 PM & 6:00-8:00 PM, Wednesday, June 20, 2007 10:00 AM-4:00 PM, Thursday, June 21, 2007		
Room	Wednesday AM	Wednesday PM	Thursday AM	Thursday PM	Friday AM
Leighton Concert Hall	EMC Plenary Lecture/Student Awards				
102	Session C: III-Nitride Electronic Devices	Session H: III-Nitride Growth and Characterization of Optical Devices	Session N: Contacts to Wide Bandgap Semiconductors	Session U: Indium Nitride	Session BB: III-Nitride Processing and Characterization
126	Session A: Chemical and Biological Sensors I	Session F: Germanium and Silicon Nanowires	Session L: Materials Integration and Flexible Thin Film Electronics	Session S: Metamorphic Materials: Characterization and Devices	Session Z: Molecular Electronics: Devices, Materials and Contacts
129	Session B: Organic/Inorganic Hybrid Photovoltaic	Session G: Organic Thin Film and Crystalline Transistors	Session M: Oxide Thin Film Integration I	Session T: Semiconductor Processing: Oxidation, Passivation	Session AA: Oxide Thin Film Integration II
131	Session E: Non-Destructive Testing	Session J: Thermoelectric and Thermionic Heterostructures and Devices	Session P: Chemical and Biological Sensors II	Session W: Spin-Dependent (or Spintronic) Electronic Materials	Session DD: Narrow Gap Materials and Devices
138		Session K: Silicon Carbide: Devices and Processing	Session Q: Silicon Carbide: Defects and Growth	Session X: Graphene and Carbon Nanotubes	Session EE: Epitaxy for Devices Session FF: III-Nitride: Pseudo-Substrates
141			Session R: ZnO Growth: Films and Nanostructures	Session Y: ZnO: Characterization and Devices	Session GG: Dilute Nitride Semiconductors
155	Session D: Spin in Low Dimensional Systems	Session I: Growth and Processing of Nanostructured Materials	Session O: Nanostructure Physics and Characterization	Session V: Thermoelectric Materials	Session CC: Compound Semiconductor Nanowires