Monday Morning, October 31, 2005

Electronic Materials and Processing
Room 310 - Session EM+NS-MoM

Novel Approaches in Wide Bandgap Semiconductors
Moderator: C.R. Eddy Jr., U.S. Naval Research Laboratory

8:20am **EM+NS-MoM1 Halide Chemical Vapor Deposition of SiC Crystals***, **M. Skowronski**, A.Y. Polyakov, H.J. Chung, S. Nigam, S.W. Huh,* Carnegie Mellon University*; M.A. Fanton,* Pennsylvania State University **INVITED**

A novel approach to the high growth rate deposition of silicon carbide single crystals and layers is described. The Halide Chemical Vapor Deposition (HCVD) process uses tetrachlorosilane, propane, and hydrogen as reactants . The use of halogenated Si source and separate injection of Si and C precursors allows for preheating the source gases up to the growth temperature (2300 K) without causing premature chemical reactions. This is a distinct advantage over approaches employing silane as the Si precursor. The stoichiometry of HCVD crystals can be controlled by changing the C/Si flow ratio and can be kept constant throughout growth, in contrast to the Physical Vapor Transport technique. HCVD allows for growth of high crystalline quality, very high purity 4H- and 6H-SiC crystals with growth rates in 0.1-0.3 mm/hr. The densities of deep electron and hole traps are determined by growth temperature and C/Si ratio and can be as low as that found in standard CVD epitaxy. At high C/Si flow ratio, the resistivity of HCVD crystals exceeds 1E5 Ohm cm. The properties of crystals grown by HCVD make an attractive method for applications in high-frequency and/or high voltage devices.

9:00am **EM+NS-MoM3 Nm-Resolution Study of Various Quantum-Well Inclusions in 4H-SiC using Ballistic Electron Emission Microscopy: Quantum-Well Energy Depth and Local Transport Behavior***, **K.-B. Park**, J.P. Pelz,* The Ohio State University*; M. Skowronski, J. Grim, X. Zhang,* Carnegie Mellon University*; M.A. Capano,* Purdue University

Thin planar inclusions with local cubic stacking can form in hexagonal SiC during device operation, processing, or growth. These have been found to behave as electron quantum wells (QWs), and strongly impact material and device property. We have used nm-resolution Ballistic Electron Emission Microscopy (BEEM)@footnote 1@ to study the electronic properties of individual "single stacking-fault (1SF)" cubic inclusions forming during p-i-n diode operation in (1 1 -2 0) oriented 4H-SiC, where the inclusions intersect a Pt Schottky Barrier (SB) interface. BEEM indicates a QW energy depth of ~0.25 eV below the host 4H-SiC for these 1SF inclusions, comparable to a previous calculated energy of ~0.22 eV@footnote 2@ and a reported ~0.282 eV energy measured by luminescence quenching.@footnote 3@ We are also currently studying inclusions of a different structure forming during CVD growth on 8° miscut n-type 4H-SiC substrates. BEEM indicates a QW energy depth of ~0.40 eV for these inclusions, between the measured ~0.25 eV depth of 1SF inclusions and the ~0.53 eV depth we previously measured on "double" SF inclusions forming during high-temperature processing@footnote 1@. We also observe that the local BEEM current amplitude and SB height on the surrounding 4H-SiC material are quite different on either side of these inclusions, possibly due to strong spontaneous polarization in 4H-SiC and/or subsurface scattering from the 8° inclined inclusion. Work supported by ONR and NSF. @FootnoteText@ @footnote 1@ Y. Ding, K. -B. Park, J. P. Pelz, K. C. Palle, M. K. Mikhov, B. J. Skromme, H. Meidia, and S. Mahajan, Phys. Rev. B 69, 041305(R) (2004).@footnote 2@ H. Iwata et al., Mater. Sci. Forum 389-393, 533 (2002).@footnote 3@ S. G. Sridhara et al., Appl. Phys. Lett. 79, 3944 (2001).

9:20am **EM+NS-MoM4 Quantitative Assessment of Diffusivity and Specularity of Textured Surfaces for Light Extraction in Light-Emitting Diodes***, **Y.A. Xi**, X. Li, J.K. Kim, F. Mont, Th. Gessmann, H. Luo, E.F. Schubert,* The Future Chips Constellation

Light extraction in GaN-based light-emitting diodes (LEDs) is limited by the large difference of the refractive index between GaN and the ambient material. The texturing of surfaces and interfaces can improve the light-extraction efficiency into the surrounding medium. Surface-textured reflectors fabricated by natural lithography and ion-beam etching are shown to have a specular as well as a diffusive component of the reflectivity. The diffusely reflected power and the specularly reflected power of surface-textured reflectors are measured and analyzed quantitatively in terms of a new theoretical model. The diffusivity, that is diffusive-power-to-total-power ratio, is determined and shown to strongly depend on the surface texture. Diffusivities of 38.1% and 42.8 % are obtained for the reflectors masked with 445 nm and 740 nm nano-polystyrene balls, respectively, much higher than the 0.35 % of a planar Silver reflector. The light-extraction efficiency from a waveguide, clad by a partially diffuse reflector, is analyzed and shown to be enhanced. In addition, the spatial transmittance pattern of the textured surface is also measured and analyzed by using the same theoretical model. Our study shows that this model can be used to quantitatively assess the dependence of the light-extraction efficiency on the diffusivity of textured surfaces in GaN-based LEDs.

9:40am **EM+NS-MoM5 MOCVD Growth of Al-rich AlGaN Alloys: Materials for Deep-UV Emitters***, **A.A. Allerman**, M.H. Crawford, S.R. Lee, D.M. Follstaedt, P.P. Provencio, K.H.A. Bogart, A.J. Fischer,* Sandia National Laboratories **INVITED**

Solid-state light sources emitting at wavelengths less than 300nm would enable technological advances in many areas such as fluorescence-based biological agent detection, non-line-of-sight (NLOS) communications, water purification, and industrial processing. Emitters achieving such emission wavelengths have been fabricated using, almost exclusively, Al-rich alloys of AlGaN. However the growth of Al-rich AlGaN alloys, and especially AlN, has proven problematic owing to their extreme sensitivity to growth conditions in addition to the lack of a native substrate. Even though AlN substrates are being developed commercially, nearly all LEDs emitting in the deep UV are grown on sapphire substrates. Typical LED structures start with an AlN buffer layer which establishes much of the basic crystal structure for the device. The AlN layer typically exhibits threading-dislocation densities exceeding 1x10@super 10@cm@super -2@ and will experience stress-induced cracking when the layer exceeds approximately 1µm in thickness. In this presentation, we will describe a method for AlN film growth that produces threading-dislocation densities less than 5x10@super 9@cm@super -2@. This method involves manipulation of growth conditions following initial film nucleation and has been used to grow crack-free AlN films exceeding 3µm in thickness. Using these AlN films as template layers, we produced Si-doped AlGaN films (with ~50-70% AlN mole fractions) that have improved electron mobilities and higher doping efficiencies. These improvements suggest a reduced level of compensation in the AlGaN film due to reductions in dislocation density. The presentation will also include the performance of LEDs emitting in the deep UV (<300nm) that have been fabricated with lower dislocation density AlN-AlGaN films. Sandia is a multiprogram laboratory operated by Sandia Corporation, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-ACO4-94AL85000. This work is also supported by DARPA under the SUVOS program managed by LTC J. Carrano.

10:20am **EM+NS-MoM7 High Reflectance GaN-based Distributed Bragg Reflectors Grown on Si Substrates***, **M.A. Mastro**, R.T. Holm, N.D. Bassim, D.K. Gaskill, C.R. Eddy Jr., R.L. Henry, M.E. Twigg,* U.S. Naval Research Laboratory

Presently, GaN based optoelectronic devices are primarily grown on expensive sapphire and SiC substrates. Substituting these substrates with inexpensive Si substrates would represent a major shift in the economics of the visible optoelectronic market. The primary limitation to this device structure is light absorption by the opaque Si substrate. Insertion of a high reflectance distributed Bragg reflector (DBR) between the substrate and the active region would increase light extraction by approximately a factor of two. The second major impediment to this device structure is the poor quality of group III-nitride films grown on Si substrates. High densities of dislocations and cracks can form in the (Al,Ga,In)N layers due to their large lattice and thermal expansion mismatch with the Si substrate. Thus low internal quantum efficiency is commonly observed for GaN based devices grown on Si substrates. This paper presents the first high-reflectance (>90%) (Al,Ga)N quarter-wave DBR grown on a Si (111) substrate. In-situ reflectometry of the MOCVD growth process allowed exact control of each individual layer thickness to yield DBR reflectance approaching the calculated theoretical level. Nominally crack free structures were obtained by controlling the distribution of the strain in the structure. Specifically, the DBR structure acted as a distributed buffer layer (DBL) for the thick GaN cap layer. TEM revealed a fall-off in screw-type dislocations throughout the DBL. This development presents the opportunity to significantly advance GaN based optoelectronics, including light emitting diodes (LEDs), resonant cavity light emitting diodes (RCLEDs) and vertical cavity surface emitting lasers (VCSELs), on Si substrates.

10:40am **EM+NS-MoM8 Synthesis of Aligned Arrays of III-Nitride Nanowires and Heterostructure Nanowires via MOCVD*, G.T. Wang*,** *J.R. Creighton, P.P. Provencio,* Sandia National Laboratories*; D. Werder,* Los Alamos National Laboratory

Nanowires based on the direct bandgap semiconductor Group III nitride (AlGaInN) materials system are attractive due to their potential in novel optoelectronic applications, including LEDs, lasers, high power transistors, and sensors. We have employed a MOCVD process to synthesize highly aligned arrays of single-crystalline GaN nanowires in a standard cold-wall rotating disk reactor on 2-inch diameter sapphire wafer substrates without patterning or the use of a template. Building on this process, we have also been able to synthesize novel core-shell heterostructure nanowires consisting of a GaN cores and various III-nitride shell materials, including AlN, InN, and AlGaN, and InGaN. In this presentation, several challenges and issues regarding control of the growth process will be discussed, including selectivity of VLS growth versus film nucleation, control of nanowire alignment and density, as well as the ability to control shell-layer uniformity in heterostructure nanowires will be discussed. Data on the optoelectronic and electrical properties of the nanowires and heterostructure nanowires will also be presented. The growth processes and reactor environment employed in this study are typical of those used to synthesize device-quality III-nitride films and should be scalable to larger commercial reactors and substrates. 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.

11:00am **EM+NS-MoM9 Large-scale Synthesis of GaN Nanowires by Direct Reaction of Gallium with Ammonia*, C.-H. Hsieh,*** National Tsing Hua University, Taiwan, R.O.C.*; L.-J. Chou,* National Tsing Hua University, Taiwan, R.O.C., Taiwan, R.O. C.

High-density GaN nanowires were synthesized on a large-scale Si substrate by direct reaction of metal gallium vapor under ammonia and hydrogen gases at 680~700°C. The morphology, composition and crystal structure were characterized by field-emission scanning electron microscope (FESEM, JSM-6500F), field-emission transmission electron microscope (FETEM, JEM-3000F) and X-ray spectrometer (SHINMADZU), respectively. From SEM images, the morphology of GaN nanowires is vermicular-like with average diameter of 200 nanometer and the length of up to 20 micrometer. The compositional line profile of TEM analysis revealed the vermicular-like GaN nanowires were uniformly doped with silicon and oxygen. The correspondent electron diffraction pattern indicated the vermicular-like GaN nanowires exhibiting poly-crystal structure. The XRD results of vermicular-like GaN nanowires show the hexagonal wurtzite structure. Furthermore, the cathodoluminescence (CL) characteristics demonstrate a broad band in the energy range of 2.1-3.1eV.

11:20am **EM+NS-MoM10 Optical and Ellipsometric Studies on InN Layers Grown by High-Pressure CVD*, N. Dietz*,** *M. Alevli, M. Strassburg, V.T. Woods, U. Perera,* Georgia State University*; N.A. Stoute,* North Carolina State University, US*; D.E. Aspnes,* North Carolina State University

The fabrication of emerging detector and emitter structures as well as high-frequency/high-power devices operating at high temperature(s) that are based on group III-nitride compound alloys is presently limited by the challenging difficulties in the growth of high quality In-rich group-III-nitride alloys and heterostructures. Even though recent improvements in MBE-grown InN material established a band gap near 0.65 eV, other data show a band gap near 1.85 eV. The origin of this bandgap difference is not understood. Here, we focus on the analysis of optical data obtained both by absorption spectroscopy and spectroscopic ellipsometry (SE) on InN material grown by high-pressure chemical vapor deposition (HPCVD) in the 10 to 15 bar pressure range as a function of growth temperature, flow rate, and flow ratios of ammonia and trimethylindium (TMI). With HPCVD we can compensate the inherent volatility of nitrogen and stabilize indium-rich conditions and grow group-III-nitride alloys at temperatures comparable to those used for GaN and AlN. The optical data indicate that the decrease in optical absorption edge from 1.85 eV to 0.63 eV is caused by a series of absorption centers appearing at 1.6 eV, 1.35 eV, 1 eV, 0.87 eV and below 0.65 eV. The appearance of these centers correlates with the indium-to-nitrogen ratio, which is controlled through the flow rates of ammonia and TMI. For InN layers grown near 1100 K and molar ammonia/TMI ratios less than 200, an InN absorption edge below 0.63 eV is observed. For material with absorption edges near 1.9 eV a strong peak is observed, which appears to be excitonic in nature.

11:40am **EM+NS-MoM11 Determining Composition of HPCVD Indium Nitride with Auger Electron Spectroscopy*, R.P. Bhatta,*** *B.D. Thoms, V.T. Woods, M. Alevli, N. Dietz,* Georgia State University

Indium Nitride (InN), a wurtzite structure III-V semiconductor with a direct bandgap, has potential for use in many optoelectronic applications. In addition, alloys of InN, GaN, and AlN cover a large spectral range from 0.6 eV up to 6 eV which can be utilized in many novel optoelectronic devices. The low growth temperatures usually needed for growth and stability of InN have limited the use of widely varying alloy compositions in the same device. High pressure chemical vapor deposition (HPCVD) allows InN to be grown at temperatures similar to those of GaN and AlN. There has recently been considerable debate regarding the value of the energy bandgap of InN and its relationship to the concentration of oxygen in the film. The optical analysis of InN layers grown under HPCVD shows that the shift of the absorption edge down to 0.63 eV is caused by a series of absorption centers. The appearance of these absorption centers is closely related to the indium and nitrogen point defect chemistry, which can be controlled through the molar flow ratio of the precursors. In this contribution, the compositional analysis of HPCVD grown InN films by Auger Electron Spectroscopy (AES) is presented. The proximity of the nitrogen and indium AES peaks makes determination of nitrogen to indium ratios more difficult. It has been reported that ion sputtering reduces the nitrogen content in InN films. While this study also reports that sputtering reduces the relative peak-to-peak height for dN/dE spectra, a substantial reduction is not observed in the relative integrated intensities for undifferentiated spectra. We conclude that sputtering has a large effect on the lineshape of nitrogen AES peaks but does not substantially reduce the nitrogen concentration. The concentrations of contaminants such as carbon and oxygen were analyzed and correlated with film properties measured by Raman and absorption spectroscopy.

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