Electronic Materials and Processing Division
Room 316 - Session EM+SE-TuM

Critical Issues in Widebandgap Semiconductors

Moderator: M.R. Melloch, Purdue University

8:20am **EM+SE-TuM1 Gallium Nitride Structures for High Power Microwave Amplification**, ***L.F. Eastman***, *K. Chu, N. Weimann, J. Smart, J.R. Shealy,* Cornell University **INVITED**

Among the wide band-gap materials Gallium Nitride has yielded the best frequency response and efficiency for microwave amplifiers. Wurtzite Al@sub x@Ga@sub 1-x@N/GaN/SiC HEMT structures, with x < .50, yield a high two-dimensional electron gas density of ~ 1 x 10@super 13@/cm@super 2@ with no intentional doping, due to the piezoelectric effect. The drain-source breakdown voltage at pinchoff rises linearly with gate length, being > 200 V for 1 µm gates due to the 3-4 MV/cm breakdown field strength. Using SiC substrates having > 3 W/cm°K thermal conductivity, up to 20 W/mm periphery will be possible. The normalized drain current is > 1 A/mm, yielding a high normalized optimum load of ~ 200 ohm-mm for 1 µm gates. Large periphery HEMT's with reasonable load resistances will allow power levels > 100 W, with efficiency above 60%, for frequencies < 12 GHz. The impact of dislocations, with density of .5 - 2.0 x10@super 9@/cm@super 2@ for GaN on SiC, on electron mobility has been determined analytically, and is in the range of 1,500-2,000 cm@super 2@/V-s. These dislocations line up in the growth direction and thus do not substantially limit the electron mobility in vertical FET's such as the Static Induction Transistor (S.I.T.) The theoretical value of the peak electron velocity for GaN is 2.7 x 10@super 7@cm/s and is reached at 150-200,000 V/cm. Short gate (.15µm) HEMT's have unity current gain frequency of ~ 70 GHz, and unity power gain frequency of 140 GHz. Due to the large bandgap, operation with channel temperatures > 200°C is possible with no substantial reduction in performance.

9:00am **EM+SE-TuM3 HfN Films Grown on GaN by Reactive MBE using Ammonia@footnote 1@**, ***A. Parkhomovsky***, *B.E. Ishaug, A.M. Dabiran, P.I. Cohen,* University of Minnesota

Stoichiometric HfN has a sodium chloride structure which is lattice matched to GaN to within 1%, assuming a 45 degree rotation. It has a low work function and hence should be an abrupt ohmic contact to wide bandgap semiconductors that is stable at very high temperatures. In this work we report the epitaxial growth of HfN on the (000-1) plane of GaN thin films. Hf and Hf-N thin films of various nitrogen contents were grown by MBE using a Hf electron beam source and an ammonia leak. The films were studied using RHEED and AFM. It was found that epitaxial HfN could be grown on GaN even at room temperature. However, the surface morphology and structure are dependent upon the nitrogen content and on the substrate temperature. GaN films of about 0.2 microns thickness, also grown using ammonia, were used as the substrate for the HfN growth. The GaN was grown under conditions of excess ammonia. The surface was annealed in ammonia as the temperature was lowered, producing an N termination on this polarity. Hf and HfN were then deposited on top of GaN at temperatures between 20C and 730 C. Deposition of pure Hf at room temperature revealed an epitaxial, though bulk diffraction pattern. This was only slightly affected by annealing in vacuum to 700 C. Little change was observed when annealed in an ammonia flux. However, when Hf was deposited in an ammonia flux at room temperature, the diffraction pattern corresponding to HfN is observed. For this room temperature film, there is some evidence of faceting in the diffraction pattern. AFM indicated an rms roughness of 5 nm for 100 nm film. If HfN was deposited at substrate temperatures above 350 C, a polycrystalline diffraction pattern was observed. This consisted of arcs at the intersection of the Ewald sphere, which were not continuous, indicating some preferential ordering in the film. AFM indicated an rms rougnhness of 40 nm for a 100 nm film. The electrical properties of the contact as well as the role of the interfacial termination and the flux ratio on the film growth will be presented. @FootnoteText@ @footnote 1@Partially Supported by Air Force Office of Scientific Research and the Office of Naval Research.

9:20am **EM+SE-TuM4 Investigation of Metal / GaN Interface Properties using Photoemission Spectroscopy and I-V Measurements**, ***C.I. Wu***, *A. Kahn,* Princeton University

We present a systematic investigation of the formation of Schottky barriers between n- and p-GaN grown by MOCVD and a series of high and low work function metals (Mg, Al, Ti, Au and Pt). We compare interface Fermi level positions with measured transport characteristics (I-V). The interfaces are formed on well ordered (0001)-(1x1) surfaces. The initial band bending is 0.75 eV upward and 0.75 eV downward on clean n- and p-type surfaces, respectively. The chemistry and electronic properties of these interfaces are studied by x-ray photoemission spectroscopy (XPS) and ultraviolet photoemission spectroscopy (UPS). Al, Ti and Mg are found to react at room temperature with nitrogen, as indicated by the appearance of a free Ga component in the Ga 3d core level spectrum, whereas Au and Pt form abrupt, unreacted interfaces. The Fermi level movements on both n- and p-GaN are consistent with the metal work functions, but limited by surface or interface states. The maximum metal induced band bending is 0.9 eV downward for Mg on p-GaN and 0.8 upward for Pt on n-GaN. Upon annealing, the incorporation of Mg increases the density of acceptors as seen on both n- and p-GaN. In spite of similar work functions and chemical reaction with nitrogen, Ti and Al form drastically different Schottky barriers. Ti causes an additional band bending of more than 0.5 eV for both n- and p-GaN whereas the Al-induced band shift is less than 0.2 eV. The difference is due to very different products of reaction, i.e. AlN is a wide band gap semiconductor whereas TiN is a metallic compound. The Schottky barrier heights are 1.2 eV (1.45 eV) and 1.1 eV (0.7 eV) on n- and p-GaN, respectively, for Au (Pt). We will present on-going measurements on the comparison between Schottky barrier heights obtained by photoemission spectroscopy and I-V measurements.

9:40am **EM+SE-TuM5 Mg Doping Studies of ECR-MBE GaN Thin Films**, ***I.E. Berishev***, *E. Kim, O. Kameli, D. Starikov, A. Bensaoula,* University of Houston

MBE of GaN is a rapidly progressing ultra high vacuum growth technique that allows the growth of high purity materials, at lower temperatures, in a clean and well characterized environment, and at high enough growth rates. Much of the recent work however was performed using RF nitrogen sources instead to previously popular ECR sources. Lower deposition rates for ECR sources being the major reason. In all growth technologies, p-type doping remains an issue for GaN device structures fabrication such as LED, LD, FET, etc. As grown p-type MBE GaN layers were however successively realized by several groups. In our study a modified ASTEX ECR source, allowing optically active GaN thin films at growth rates up to 1 micron per hour, was utilized in an MBE environment. Using this nitrogen source, Mg doping studies of GaN were undertaken. The effects of growth parameters and ECR source design on the Mg incorporation and its electrical activity were characterized by SIMS, electrochemical profiling, and photo-luminescence. The background concentration and major impurities are identified by time of flight SIMS. A direct correlation exists between Mg incorporation and the ECR power, nitrogen flow, Mg cell temperature, growth temperature and ECR exit aperture size. Using an optimized process, SIMS show sharp profiles between doped and undoped layers can be obtained. This work was supported by funds from a NASA cooperative agreement #NCC8-127 to SVEC, a Texas Advanced Research Program Grant # 1-1-27764, and a Texas Advanced Technology Program Grant # 1-1-32061.

10:00am **EM+SE-TuM6 Deposition of AlN Gate Dielectrics**, ***B. Gila***, *S.M. Donovan, C.R. Abernathy, K.N. Lee, J.D. MacKenzie, F. Ren, S.J. Pearton,* University of Florida, Gainesville*; S.N.G. Chu,* Bell Laboratories, Lucent Technologies

The development of a suitable insulator for GaN is a critical step in developing a GaN MOSFET technology. Conventional dielectrics such as SiO@sub 2@ and Si@sub 3@N@sub 4@ have generally failed on III-V materials because of high interface state densities. AlN is an attractive alternative because of its large bandgap, high thermal conductivity and excellent thermal stability. Also, a high relative dielectric constant (8-9) alleviates the problem of high fields in the dielectric in high voltage applications. AlN has also been proposed as a potential replacement for silicon dioxide in high temperature MIS based silicon carbide device applications. In this study, 375Å AlN films were deposited in ultrahigh vacuum (UHV) using an RF nitrogen plasma and dimethylethylamine alane (DMEAA) on Si, SiC and GaN/Sapphire at temperatures ranging from 325° to 525°C. Prior to deposition various surface cleans were employed including hydrogen plasma exposure, BOE (Si) high temperature exposure to ammonia and nitrogen plasma (GaN and SiC). Cross-sectional TEM (XTEM), Auger electron spectroscopy (AES), reflection high energy electron diffraction (RHEED), C-V and I-V analysis were used to characterize the films as functions of deposition temperature and surface preparation. In spite of the low deposition temperatures, none of the films were found to contain oxygen or carbon within the detection limit of AES. Consequently, the reverse breakdown characteristics of the layers were found to be excellent.

By contrast, the interface state density as measured by C-V was found to depend strongly on the nature of the initial substrate surface. Optimization of the initial starting surface via mass spectrometry and RHEED during in-situ chemical cleaning produced substantial reduction in the interfacial leakage current. As a result, initial GaN HIGFET devices show promising performance with improved breakdown and C-V behavior relative to conventional MESFET structures.

10:20am **EM+SE-TuM7 Progress in SiC: From Material Growth to Commercial Device Development**, ***C.H. Carter***, *V.F. Tsvetkov, D. Henshall, O. Kordina, K. Irvine, R. Singh, S.T. Allen, J. Palmour,* Cree Research, Inc. **INVITED**

Silicon carbide technology has made tremendous strides in the last several years, with a variety of encouraging device and circuit demonstrations in addition to volume production of nitride-based blue LEDs being fabricated on SiC substrates. The commercial availability of relatively large, high quality wafers of the 6H and 4H polytypes of SiC for device development has facilitated these exciting breakthroughs in laboratories throughout the world. These have occurred in numerous application areas, including high power devices, short wavelength optoelectronic devices, and high power/high frequency devices. This presentation will describe progress made in increasing the quality and size of SiC wafers, advances in SiC epitaxy and some of the resulting device demonstrations and commercialization by Cree Research. To meet the challenges required for commercialization of SiC semiconductors, we have made specific efforts towards larger diameter high quality substrates which have led to production of 50 mm diameter 4H and 6H wafers for fabrication of LEDs and the demonstration of 75 mm wafers. The latest results on micropipe reduction will be presented including a wafer which contains a total of 7 micropipes, yielding a density of 0.7 cm@super-2@. High voltage P-i-N diodes have been fabricated from hot-wall grown epitaxy using junction termination extension (JTE) edge termination. The highest breakdown voltage achieved for these diodes is >5.5 kV, which is a new world record for blocking voltage for a SiC device. In the microwave device area, a SiC MESFET with 42 mm of gate periphery on a single die which had a maximum RF output power of 53 watts CW with 37% power-added efficiency (PAE) at 3.0 GHz has been demonstrated. This unprecedented power from a die with an area of only 3 mm@super2@ demonstrates the extremely high power handling capability of SiC microwave devices. Additionally, SiC MESFETs showing 2.5 W/mm with 41% PAE at 8 GHz, demonstrate the utility of this technology at X-band.

11:00am **EM+SE-TuM9 Critical Development Issues for Deep (10 to 100 µm) Etching of SiC**, *D.C. Sheridan,* Auburn University; ***J.B. Casady,*** Northrop Grumman; *C.E. Ellis,* Auburn University; *R.R. Siergiej,* Northrop Grumman; *J.D. Cressler,* Auburn University; *W.E. Urban, W.F. Valek, H. Buhay,* Northrop Grumman

Silicon carbide is a wide bandgap (3.2 eV for the 4H polytype) semiconductor gaining popularity in applications requiring high-power, high-frequency, and high-temperature performance@footnote 1@. Material quality improved significantly since the first commercial release of SiC substrates in 1991. Numerous SiC semiconductor devices have been developed, such as thyristors, diodes, JFETs, MESFETs, and static induction transistors. Because of its high bond strength, the etching of SiC has been quite difficult, performed almost exclusively using dry etching techniques. Most techniques have utilized fluorinated gas chemistries in reactive ion etch (RIE), electrocyclotron resonance (ECR) etch, or inductively coupled plasma (ICP) etch systems. Residue free etches have been developed with etch rates from 5 nm/minute up to 350 nm/minute@footnote 2,3@. For very deep etching of SiC, up to 75 µm, which would be required for selected applications, no suitable process has been reported on. The ideal process would optimize a combination of fast etch rate, good mask selectivity, and reproducibility. In this work, we compare five SiC etches used in commercial RIE systems with regard to the above criteria. The SiC etches examined are all residue-free, and posses etch rates ranging from 8 nm/minute up to 160 nm/minute. The etches utilize one or more of the following fluorinated gases: NF@sub 3@, SF@sub 6@, CHF@sub 3@, or CF@sub 4@. A more detailed characterization of the etch recipes will be given in the full paper, and partial details have been reported elsewhere@footnote 4,5,6@. Several inorganic and organic mask materials will also be evaluated. Each mask material is characterized and tabulated in terms of etch rate, selectivity, and residue-formation for each of the SiC etches. @FootnoteText@ @footnote 1@ J.B. Casady and R.W. Johnson, Solid-St. Elect., Vol. 39, No. 10, p. 1409, 1996. @footnote 2@ P.H. Yih, V. Saxena, and A.J. Steckl, Phys. Stat. Sol. (b) Vol. 202, p. 605, 1997. @footnote 3@ G. McDaniel, J.W. Lee, E.S. Lambers, S.J. Pearton, P.H. Holloway, F. Ren, J.M. Grow, M. Bhaskaran, and R.G. Wilson, J. Vac. Sci. Technol. A, Vol. 15 @footnote 4@ J.B. Casady, E.D. Luckowski, M. Bozack, D. Sheridan, R.W. Johnson, and J.R. Williams, J. Electrochem. Soc., Vol. 143, No. 5, p. 1750, 1996. @footnote 5@ P.H. Yih and A.J. Steckl, J. Electrochem. Soc., Vol. 140, p. 1813, 1993. @footnote 6@ J.B. Casady, S.S. Mani, R.R. Siergiej, W. Urban, V. Balakrishna, P.A. Sanger, and C.D. Brandt, J. Electrochem. Soc., Vol. 145, No. 4, p. L58, 1998.

11:20am **EM+SE-TuM10 Thermochemical Stability of Plasma-Deposited Silicon Oxycarbide Thin Films Subjected to Post-Deposition Rapid Thermal Annealing**, ***D.M. Wolfe***, *B. Ward, F. Wang, M. Xu, G. Lucovsky, R.J. Nemanich, D.M. Maher,* North Carolina State University

Low defect density gate dielectrics are of critical importance to maximize electrical performance/reliability in SiC high power devices. Under some growth conditions carbon atoms are trapped in thermally-grown oxides forming silicon oxycarbides@footnote 1@, and it has been suggested that these C-atoms degrade device performance. The bonding of C-atoms in silicon oxycarbides as well as their thermal stability is therefore addressed. Thin silicon suboxide (SiO@sub x@, x<2) and silicon oxycarbide (SiO@sub x@C@sub y@, x<2, y<<1) films were deposited at 250°C by remote-plasma enhanced CVD. Changes in the local chemical bonding and the onset of crystallization upon rapid thermal annealing at temperatures from 600-1100°C were investigated. XPS and RBS were used for compositional analysis; FTIR was used to track the extent of structural/chemical changes through shifts in Si-O and Si-C bond-stretching frequencies. Raman spectroscopy, and HRTEM/selective area diffraction were used to monitor crystallization products through the appearance of characteristic phonon modes and diffraction patterns, respectively. These studies showed a structural/chemical transformation occurred at about 900°C for silicon suboxide films. At this temperature, the end-product material was comprised of Si nanocrystals imbedded in an non-crystalline SiO@sub 2@ matrix. A similar structural/chemical transformation, in which Si nanocrystals were also formed, was observed between 1000 and 1050°C for the silicon oxycarbides. However, a siloxane-type Si-O-C bond was observed to form at intermediate temperatures (~900°C), and to disappear upon crystallization. No evidence for amorphous or crystalline C-C bonds, or other C-O bonding groups was found in the oxycarbide films before, or after annealing. Finally, concentrations of Si and O, and Si, O and C remained essentially the same for the respective as-deposited and fully-annealed films. @FootnoteText@ @footnote 1@ B. Hornetz, H-J. Michel, J. Halbritter, J. Mater. Res 9, 3088 (1994).

Electronic Materials and Processing Division
Room 316 - Session EM+PS+SE-TuA

Plasma Processing of Compound Semiconductors
Moderator: C. Eddy, Boston University

2:00pm **EM+PS+SE-TuA1 Thermally Induced Improvements on SiN@sub x@:H/InP Devices**, ***E. Redondo***, *N. Blanco, I. Mártil, G. González Díaz,* Universidad Complutense de Madrid, Spain*; R. Peláez, S. Dueñas, H. Castán,* Universidad de Valladolid, Spain

The electron cyclotron resonance (ECR) plasma technique has been recently proved to be optimum as insulator deposition method in Al/SiN@sub x@:H/InP devices.@footnote 1@ In this communication we present a study of the influence of rapid thermal annealing (RTA) treatments on the interface characteristics of Al/SiN@sub x@:H/InP devices. The insulator was obtained by the ECR plasma method at 200°C-deposition temperature. The films were deposited in two steps: we deposited first a film with x=1.55 and then another with x=1.43. Total film thickness was 500Å in one set of samples and 200Å in other. RTAs were conducted in Ar atmosphere during 30s in a temperature range between 400 and 800°C. The electrical characteristics of the devices have been obtained by capacitance-voltage (C-V) and deep-level transient spectroscopy (DLTS) measurements. Those films annealed between 400 and 500°C/30s in Ar atmosphere give structures with the minimum interfacial trap density. The interface trap density behavior with the annealing temperature has been observed to show the same trend with both CV and DLTS measurements, reaching lower values in the latest ones. The minimum interfacial trap density value achieved with the best annealing is of 3x10@super 11@ cm@super -2@ eV@super -1@, obtained for 400°C/30s annealing on the thinnest structure (200Å). Besides, DLTS measurements show the presence of features in the spectrum that are characteristic of phosphorus vacancies, V@sub p@, and deep centers. The annealing at 400°C/30s reduces the V@sub p@ content. This suggests that the nitrogen from the insulator is filling these vacancies so InP surface is being passivated. @FootnoteText@ @footnote 1@ S.García, I.Mártil, G.González Díaz, E.Castán, S.Dueñas, M.Fernandez. J.Appl.Phys, 83 (1), 1998, pp 600-603.

2:20pm **EM+PS+SE-TuA2 Damage to III-V Devices During Electron Cyclotron Resonance Chemical Vapor Deposition**, ***F. Ren***, University of Florida, Gainesville*; J.W. Lee, D. Johnson, K. McKenzie,* Plasma-Therm, Inc.*; T. Maeda, C.R. Abernathy, Y-.B. Hahn, S.J. Pearton,* University of Florida, Gainesville*; R.J. Shul,* Sandia National Laboratories

GaAs-based metal semiconductor field effect transistors (MESFETs), heterojunction bipolar transistors (HBTs) and high electron mobility transistors (HEMTs) have been exposed to ECR SiH@sub 4@/N@sub 2@, SiH@sub 4@/N@sub 2@O and SiH@sub 4@/NH@sub 3@ discharges for deposition of SiN@sub x@ or SiO@sub 2@ passivating layers. The effect of source power, rf chuck power, pressure and plasma composition have been investigated. Effects due to both ion damage and hydrogenation of dopants are observed. For both HEMTs and MESFETs there are no conditions where substantial increases in channel sheet resistivity are not observed, due primarily to (Si-H)@super o@ complex formation. In HBTs the carbon-doped base layer is the most susceptible layer to hydrogenation. Ion damage in all three devices is minimized at low rf chuck power, moderate ECR source power and high deposition rates.

2:40pm **EM+PS+SE-TuA3 Anisotropic Etching of InP using CAIBE (Cl@sub 2@/Ar): Importance of the Sample Temperature Stability and the Reactive Gas Distribution**, ***B. Lamontagne***, *M. Gagnon, J. Stapledon, P. Chow-Chong, M. Davies,* National Research Council, Canada

Process development has been performed for the dry etching of InP using our Chemically Assisted Ion Beam Etching (CAIBE) system (Ionfab 300 from Oxford Inst.). We studied the etching mechanisms in order to obtain vertical, deep and smooth InP sidewalls. Such etching profiles are essential for optoelectronic discrete devices such as turning mirrors, reflector gratings, deeply etched waveguides, etc. The CAIBE system has a 15 cm diameter R-F driven ion source, the ion beam is usually composed of argon while chlorine is introduced through the gas ring located in front of the heated platen. The sample temperature - a critical parameter when etching InP with chlorine - has been calibrated and monitored using a non-contact sensor: a diffuse reflectance spectrometer (DRS 1000 Thermionics Northwest Inc.). It gives an accurate temperature measurement of the sample itself using the shifting effect of the temperature on the absorption edge position of semiconductors. This diagnostic tool allowed us to monitor the sample temperature increase under ion bombardment (CAIBE process) for various conditions; sample heating and mounting technique, ion beam current and energy. In some extreme process conditions the sample temperature has increased from 20° C to 300° C in less than one minute. Our results point out the need to use a stable process temperature in order to obtain vertical sidewalls. The influence of the reactive gas distribution has also been investigated, for example, by modifying the gas ring design. Etching conditions characterized by vertical (>89°) and long (up to 15 µm) sidewalls and SiO@sub 2@ mask selectivity of 30 were obtained.

3:00pm **EM+PS+SE-TuA4 Hydrogen in Compound Semiconductors**, ***M.D. McCluskey***, *N.M. Johnson,* Xerox Palo Alto Research Center **INVITED**

Hydrogen can be inadvertently introduced at any of several steps in the fabrication of optoelectronic devices. In particular, incorporation of hydrogen can occur during growth, wet chemical processing, or dry etching. The most common consequence of hydrogenation is the passivation of dopant impurities, which leads to a decrease in the electrical conductivity of the material. The most successfully applied experimental technique for directly determining the involvement of hydrogen has been infrared-absorption local vibrational mode (LVM) spectroscopy, which will be illustrated with representative examples. In GaN:Mg grown by metalorganic chemical vapor phase deposition, hydrogen passivates Mg acceptors during the growth. Through experimental and computational studies it has been determined that hydrogen incorporated during growth forms electrically inactive complexes with Mg, and that a furnace anneal dissociates these complexes to activate the acceptor dopant. LVM spectroscopy was essential in the identification of the Mg-H complex. The observed frequency of the hydrogen LVM verified the theoretical prediction that hydrogen attaches to a host nitrogen atom. Recently, large hydrostatic pressures have been applied to compound semiconductors to probe the vibrational properties of hydrogen-related complexes. In GaAs, the pressure dependent shifts of hydrogen stretch modes provide clues about the location of hydrogen in the complexes. In AlSb, pressure was utilized to resolve a mystery as to why the Se-D complex gives rise to one stretch mode peak while the Se-H stretch mode splits into three peaks. This anomalous splitting is explained in terms of a new resonant interaction between the stretch mode and combination modes involving a wag mode harmonic and extended lattice phonons.

3:40pm **EM+PS+SE-TuA6 The Interaction of Electrons with Hydrogenated GaN(0001)**, *V.J. Bellitto,* ***B.D. Thoms***, Georgia State University*; D.D. Koleske,* Naval Research Laboratory

Although Group III nitrides have recently been used to produce blue LEDs and laser diodes, many surface properties and processes have yet to be fully understood. One issue important to many applications of these materials is the effect of hydrogen during growth and processing. For example, hydrogen has been reported to significantly affect incorporation of dopants, Group III constituents, and contaminants. We have studied GaN(0001) using low energy electron diffraction (LEED), Auger electron spectroscopy (AES), energy loss spectroscopy (ELS), and high resolution electron energy loss spectroscopy (HREELS). The ELS spectrum of GaN is seen to be particularly sensitive to exposure to atomic hydrogen (produced by a tungsten filament heated to 2073 K). A new peak appears at a loss energy of approximately 12 eV after atomic-hydrogen exposure but is not seen after exposure to molecular hydrogen alone. However, this peak is strongly affected by low energy electron irradiation of the surface. Substantial reduction in the 12 eV peak intensity is observed following exposure to 1.8 microamps of 90 eV electrons for two minutes. After 10 minutes of electron impingement on the hydrogen-atom-exposed surface, ELS spectra appear identical to those taken with no hydrogen atom exposure. Heating to 690 K is also seen to remove the hydrogen-related peak from ELS spectra. Recently, Gillis et al. have shown that simultaneous exposure of GaN to hydrogen atoms and low energy electrons results in anisotropic etching. Implications of these data for both surface science and etching of GaN will be discussed.

4:00pm **EM+PS+SE-TuA7 III-V Surface Plasma Nitridation: A Challenge for III-Nitride Epigrowth**, *G. Bruno,* ***M. Losurdo***, *P. Capezzuto,* MITER-CNR, Italy*; E.A. Irene,* University of North Carolina, Chapel Hill

A challenge in the growth and processing of III-V nitrides is the control and optimization of the substrate/epilayer interface. It has been reported that high quality epilayers of GaN and related materials can be obtained by nitridation of the sapphire and GaAs substrates before the film growth. Substrate nitridation allows to accomodate the lattice mismatch between substrates and GaN epilayers and crucially affects the cristalline quality and

structure of both the buffer and epitaxial GaN layers. In this contribution, the focus is on the nitridation process of GaAs and GaP (100) substrates to form GaN layers and of (0001) sapphire surfaces to form thin AlN. In order to elucidate the chemistry and kinetics of these solid state anion exchange reactions, the nitridation of (100) InP is also investigated. Nitridations are performed in a remote radiofrequency plasma metalorganic chemical vapor deposition (MOCVD) apparatus by exposing surfaces to the downstream flow of N@sub 2@ and N@sub 2@-H@sub 2@ plasmas, taking the advantages of low process temperatures and minimal surface damage. In situ optical diagnostics such as optical emission spectroscopy (OES) and spectroscopic ellipsometry (SE) are used to fingerprint in real time the gas phase and surface modifications, respectively. Thus, the chemistry and kinetics of the plasma-surface interactions are described toghether with the surface/interface composition and morphology. AFM analysis has been used to measure the surface roughness and to validate the effectiveness of plasma nitridation with respect to the conventional thermal nitridation by NH@sub 3@. Transmission electron microscopy (TEM) is used to highlight the different structural aspects of the nitride layers obtained by N@sub 2@ and N@sub 2@-H@sub 2@ mixtures. Optimizing the surface temperature and the N@sub 2@/H@sub 2@ ratio the formation of an interfacial As-rich layer in the GaAs/GaN growth is minimized, the nitridation depth is increased up to 15nm and compact and chemically stable GaN layers are obtained.

4:20pm **EM+PS+SE-TuA8 III-Nitride Dry Etching - Comparison of Inductively Coupled Plasma Chemistries**, ***H. Cho***, *Y-.B. Hahn, D.C. Hays, C.R. Abernathy, S.M. Donovan, J.D. MacKenzie, S.J. Pearton,* University of Florida, Gainesville*; J. Han, R.J. Shul,* Sandia National Laboratories

A detailed comparison of etch rates, etch yields, surface morphology and sidewall anisotropy has been performed for GaN, InN and AlN etched in Inductively Coupled Plasma discharges of BCl@sub 3@, BI@sub 3@, BBr@sub 3@, ICl and IBr. Etch selectivities of 100:1 for InN over GaN and AlN are obtained in BI@sub 3@ due to the relatively high volatility of the InI@sub x@ products and the lower bond strength of InN. The selectivities are much lower in the other chemistries. The etched surfaces of the nitrides are smooth over a broad range of source and chuck powers, pressures and discharge compositions, and there is typically a slight deficiency of N@sub 2@ in the near-surface (@<=@ 100Å) region. The etch yields for all of the chemistries are relatively low (@<=@ 2), indicating that the high ion flux in the ICP tool is a critical factor in obtaining practical etch rates for the nitrides.

4:40pm **EM+PS+SE-TuA9 Photoenhanced RIE of III-V Nitrides in BCl@sub 3@/Cl@sub 2@/Ar/N@sub 2@ Plasmas**, ***A. Tempez***, *N. Medelci, N. Badi, I. Berichev, D. Starikov, A. Bensaoula,* University of Houston*; A. Chourasia,* Texas A&M University

Boron nitride (BN) and gallium nitride (GaN) are known as superior semiconductor materials for UV optoelectronic and high power, high temperature applications. As a consequence of their high molecular bond strength, these materials are extremely difficult to etch. In order to address the device processing issue, reactive ion etching (RIE) tests were performed on BN and GaN thin films. Our experiments show that optimum etching occurs using BCl@sub 3@/Cl@sub 2@/Ar chemistries for GaN and Cl@sub 2@/Ar for BN. In the case of GaN, the BCl@sub 3@/Cl@sub 2@/Ar mixture results in the highest reported RIE GaN etch rates.@footnote 1@ Auger and x-ray photoelectron spectroscopy analyses of the etched surfaces always show a depletion of the surface nitrogen atomic composition which increases with the dc bias (rf power). The impurity incorporation, C and Cl also shows the same trend. In order to improve the etch rates at lower powers, a photoenhanced RIE process was investigated. A BCl@sub 3@/Cl@sub 2@/Ar/N@sub 2@ plasma in combination with a xenon arc lamp was utilized. Preliminary results show a 33% increase in GaN etch rates for a -220 V dc bias (100 W rf power). The dependence of etch rates, surface composition and chemistry, and surface morphology on dc bias (rf power) and photo-irradiation flux will be presented. In addition, the energy and angle distribution of the reaction species from nitride materials exposed to well characterized reactive beams were investigated. The results will be compared to those from RIE and Photo-RIE data and a model for the possible surface etch reactions will be discussed. This work was supported by funds from a NASA cooperative agreement #NCC8-127 to SVEC, a Texas Advanced Research Program Grant # 1-1-27764, and a Texas Advanced Technology Program Grant # 1-1-32061. This material is also based upon work supported by the U.S. Civilian Research and Development foundation under Award No. REI-247. @FootnoteText@ @footnote 1@N. Medelci, A. Tempez, E. Kim, N. Badi, I. Berichev, D. Starikov and A. Bensaoula, 1998 MRS Spring Meeting (in print).

5:00pm **EM+PS+SE-TuA10 Characteristics of Cl@sub 2@ -based Inductively Coupled Plasmas during the GaN Etching**, ***H.S. Kim***, *J.W. Jang, Y.H. Lee, G.Y. Yeom,* Sungkyunkwan University, Korea*; J.W. Lee, T.I. Kim,* Samsung Advanced Institute of Technology, Korea

Planar inductively coupled Cl@sub 2@-based plasmas have been used to etch GaN and etch properties having smooth and nearly vertical etch profiles with the etch rates close to 850 nm/min could be obtained with Cl@sub 2@-rich gas combinations. To understand the effects of plasma conditions on the GaN etch properties, The quarupole mass spectrometry(QMS), optical emission spectroscopy(OES), and an electrostatic probe have been used. Especially, the quadrupole mass spectrometer system we used in the analysis of the plasmas was configured with ion optics, energy filter, and integral electron impact ion source for plasma diagnostics. Therefore, not only the radical densities but also positive and negative ion densities and their energy distributions were also measured. As process conditions used to study the effects of plasma characteristics on the GaN etch properties, Cl@sub 2@ was used as the main etch gas and Ar, BCl@sub 3@, and CH@sub 4@ were used as additive gases. Operational pressures were varied from 5mTorr to 30mTorr while other conditions such as inductive power, bias voltage, and substrate temperature were fixed at 600 watts, -120 volts, and 70 centigrade, respectively. The relative amounts of reactive ions (Cl@super +@, Cl@sub 2@@super +@, Cl@super -@, etc.), Ga-containing etch products(GaCl, GaCl@sub 2@, and GaCl@sub 3@ for Cl@sub 2@ plasma), and nitrogen-containing etch products (N, N@sub 2@, NH@sub 3@, etc.) were estimated by the plasma mass spectrometric measurements. The results showed that the enhancement of GaN etch rate was related to the increase of Cl radical and reactive ion such as Cl@super +@, Cl@sub 2@@super +@, etc. measured by the QMS and OES during the Cl@sub 2@-based inductively coupled plasma etching. Therefore, chemical reactions between Ga in GaN and Cl and Cl@sub 2@@super +@ from Cl@sub 2@, under the sufficient ion bombardments to break GaN bonds, appear to be important in the GaN etching. More detailed analysis of plasmas and their relation to GaN etching will be given in the presentation.

Selected Energy Epitaxy Topical Conference
Room 327 - Session SE-WeM

Selected Energy Epitaxial Growth Processes
Moderator: R. Brandt

8:20am **SE-WeM1 Ab Initio Studies of the Surfaces and Growth of GaN and AlN**, ***W.A. Goddard III***, *R.P. Muller, B.L. Tsai,* California Institute of Technology **INVITED**

We have examined the reconstruction and growth of cubic GaN and AlN using Density Functional Theory with Generalized Gradient Approximations. We find stable surfaces for excess metal lead to a c(2x2) structure while stoichiometric leads to metal termination but a P(2x2) structure. Implications for growth will be discussed.

9:00am **SE-WeM3 Film Defects and Growth Dynamics in Wide Bandgap Epitaxy**, ***F.A. Ponce***, Xerox Palo Alto Research Center **INVITED**

The III-V nitride semiconductors have achieved a high degree of notoriety in the last few years.@footnote 1@ Light emitting devices based on double heterostructure InGaN/GaN films have been produced with light emission efficiencies exceeding incandescent lighting. Blue diode lasers with continuous operation for more than 10,000 hours using AlGaN/GaN/InGaN heterostructures have been reported and their commercial use is expected in the near future. The high optoelectronic performance of nitride semiconductors is related to an interesting microstructure, quite different from other semiconductors. Large dislocation densities are observed (~10@super 10@ cm@super -2@) and are associated with a columnar array of defect-free crystallites. The defect structure appears to play a key role in the relaxation of thermal stresses, typical in these materials, allowing the local growth of high quality heterostructures under otherwise unfavorable conditions. The nature of the substrate/thin film interfaces will be discussed, as well as the role of the buffer layer. Details of the dislocation arrangement and structure and correlation with light emitting properties will be presented for GaN thin films and for InGaN quantum wells. @FootnoteText@ @footnote 1@ F. A. Ponce and D. P. Bour, Nature Vol. 386, 351 (1997).

9:40am **SE-WeM5 Growth of Thin Film Materials with Supersonic Molecular Beams**, ***W. Ho***, Cornell University **INVITED**

Atomic and molecular beams have been used extensively to probe fundamental physical and chemical properties of atoms and molecules. A new application of molecular beams for materials synthesis is emerging. The unique properties of supersonic molecular beams which make this new application to thin film growth promising are described. Problems encountered in the implementation of supersonic jet epitaxy (SJE) as well as growth conditions favorable for the incorporation of real-time, in situ monitoring are discussed. The advantages and disadvantages of different precursors for the growth of cubic-SiC on Si are compared. The growth rate and morphology of the grown films are shown to depend on the kinetic energy of the precursors and the growth temperature. Enhancing the kinetic energy of precursors also led to lower growth temperatures for single crystal GaN and AlN thin films on silicon based substrates. Problems which remain to be solved in SJE of wide band gap semiconductors are summarized.

10:20am **SE-WeM7 Selected Energy Etching of Semiconductors by Electron-enhanced Surface Reactions**, ***H.P. Gillis***, *M.J. Christopher,* University of California, Los Angeles*; K.P. Martin, D.A. Choutov*,* Georgia Tech **INVITED**

It is well established that the standard ion-enhanced dry etching methods (RIE, ECR, and CAIBE) can damage the sample during etching by momentum transfer from energetic ions. The result is degradation of optical, electrical, and morphological properties of etched surfaces. We will review these energy-dependent damage mechanisms from ion-enhanced etching, and present results from an alternative approach--Low Energy Electron Enhanced Etching (LE4)--that avoids ion bombardment altogether. LE4 gives mirror smooth surfaces (RMS surface roughness 2 - 3 Angstroms) and maintains stoichiometry in compound semiconductors while giving highly anisotropic pattern transfer in micrometer and nanometer scale structures in Si, GaAs, and GaN. Special emphasis will be placed on the role of electron energy thresholds in developing selective processes and in controlling the polishing or "smoothening" of the surface during etching. @FootnoteText@ *Present address: National Semiconductors, San Jose, CA.

11:40am **SE-WeM11 Velocity, Temperature, and Chemical Composition of a dc-Arcjet Plume**, ***J.B. Jeffries***, *J. Luque, W. Juchmann,* SRI International

Laser-induced fluorescence, optical emission, and Langmuir probe measurements are used to characterize the reactive plume of a dc-arcjet reactor during diamond deposition. We find one third of the feedstock hydrogen is dissociated into atoms. Optical measurements are used to determine spatially resolved gas temperature, plume velocity, and the spatial variation of the concentrations of reactive intermediates. The atomic hydrogen concentration is not in equilibrium with the gas temperature, and finite rate chemistry controls the concentrations of the reactive intermediate species in the plume. The supersonic directed velocity of the plume produces a shock structure just above the substrate. The temperature and pressure gradient produced by this shock influences the chemical composition of the gases in the boundary layer and the transport of reactants to the surface. Supported by ARO and DARPA via the NRL.

Selected Energy Epitaxy Topical Conference
Room 327 - Session SE-WeA

Novel Sources for Selected Energy Growth
Moderator: R.B. Doak, Arizona State University

2:00pm **SE-WeA1 UHV Arcjet Atomic Nitrogen Source: Beam Characterization and GaN Epitaxial Growth**, ***F.J. Grunthaner,*** Jet Propulsion Laboratory*; R. Bicknell-Tassiuis,* Jet Propulsion Laboratory, US*; P. Deelman, P.J. Grunthaner,* Jet Propulsion Laboratory*; J. Guilani,* Naval Research Laboratory*; C.E. Bryson,* Surface/Interface, Inc. **INVITED**

2:40pm **SE-WeA3 Flow Characteristics of a UHV Nitrogen Arcjet**, ***C.H. Chang,*** Thermosciences Institute, US*; F.J. Grunthaner,* Jet Propulsion Laboratory*; R. Bicknell-Tassiuis,* Jet Propulsion Laboratory, US*; P. Deelman, P.J. Grunthaner,* Jet Propulsion Laboratory*; J.L. Giuliani, J.P. Apruzese, P. Kepple,* Naval Research Laboratory, US

Flow characteristics in the nozzle of a nitrogen arcjet have been simulated by a model. Electrons, ions, and neutral atoms and molecules are represented as separate species. Dissociation, ionization, and recombination are treated as separate reactions. Thermal non-equilibrium is represented by a two-temperature model. Energy input to plasma from the arc is modeled as a source determined by local current and electrical conductivity. Momentum and energy losses and recombinations at the nozzle wall are included as source/sink determined by fluxes to the wall. The results show essentially frozen gas-phase reactions and thermal nonequilibrium due to Joule heating of electrons and in the expansion part of the nozzle. Wall interactions have strong effects on the results, indicating that they play important roles in the flow due to very high surface area relative to the volume of the plasma. For example, plasma velocity decreases from 6000 m/s without wall interactions to 3000 m/s with modest amount of wall interactions. These results also show reasonable agreement with optical emission measurements, which confirms that the arcjet plasma is far from LTE. The spectra suggest nitrogen dissociation levels of 0.3% - 9%, depending on nitrogen flow rate and arc plasma current, which also determine the relative amounts of excited atomic and molecular nitrogen. Langmuir probe studies of the source show that electron and ion fluxes increase with increasing power, and that the ion energy distribution shifts to lower energies. Typical ion fluxes were on the order of 4E-9 A/cm@super 2@ with a maximum ion kinetic energy of 3.5eV. The median electron energy was 1eV, with a maximum of less than 4eV.

3:00pm **SE-WeA4 Gas-Phase Diagnostics for Wide Bandgap Semiconductor Development**, ***D.G. Fletcher,*** *G.A. Raiche,* NASA Ames Research Center

Efforts to develop commercially viable wide bandgap semiconductors can be aided considerably by a characterization of the atomic beam. For arcjet devices used for nitride epitaxy, this involves determining the thermochemical state of a partially dissociated nitrogen flow. Since arcjet flows of nitrogen are also used in the development of thermal protection systems for aerospace applications, laser-spectroscopic techniques have been developed for flow characterization, and this has been driven by the need to relate test results to the flight environment. Recently, two-photon laser-induced fluorescence of ground-state atomic nitrogen has been used to determine the degree of dissociation and the enthalpy distribution in a large scale arcjet facility.@footnote 1@ Based on observations from these experiments and the similarities between the arcjet devices used in nitride epitaxy and aerospace materials testing, diagnostic strategies are proposed to establish the link between electronic state populations and nitride material growth. The paper will include a discussion of recent, relevant experimental results for ground state atomic nitrogen, and will report on progress made in developing laser-diagnostic strategies for determining the populations of the two low-lying, metastable doublet states of atomic nitrogen. @FootnoteText@ @footnote 1@D.G. Fletcher "Arcjet Flow Properties Determined from Laser-Induced Fluorescence of Atomic Nitrogen", AIAA Paper No. 98-0205, Reno, NV, January, 1998.

3:20pm **SE-WeA5 Fast Deposition of Amorphous Hydrogenated Silicon and Carbon**, ***D.C. Schram,*** *M.C.M. van de Sanden,* Eindhoven University of Technology, The Netherlands **INVITED**

For solar cell and other developments faster and more efficient deposition of thin layers amorphous hydrogenated materials are necessary. With plasma beam expanding from very efficient thermal plasma sources rates of 10-100 nm/s over a large area has been studied. For a-C:H it proves that the faster the deposition the more dense the material and 100 nm/s has been reached. For a-Si:H good electronic material can be grown with rate of 10 nm/s and elevated substrate temperature (T~350 oC). A picture based on plasma fragmentation processes and surface kinetics will be discussed and illustrated with measurements on mass spectrometry, FTIR and other diagnostics.

4:00pm **SE-WeA7 Inexpensive Corona Discharge Source for the Growth of III-N Semiconductors**, ***D.C. Jordan,*** *C.T. Burns, R.B. Doak,* Arizona State University

The III-N nitrides AlN, GaN and InN are under intense study due to their wide bandgap properties. It is thought that the ideal nitrogen species for GaN growth may be the metastable A@super 3@@SIGMA@@super +@@sub u@ state of molecular nitrogen@footnote 1@. We have developed a low cost supersonic free-jet corona discharge source that produces exclusively this nitrogen species. The source consists of a quartz tube drawn to an orifice diameter in the range of 100-250 µm enclosing a tungsten or rhenium wire. A high voltage ranging between 2-2.5 kV at 5-9 mA is applied to that wire, resulting in a readily discernible bright plume at the tip of the nozzle. A custom-made refractory graphite skimmer then extracts a beam of activated species as the free-jet expands into vacuum. The beam transits a differentially pumped section then enters the deposition chamber where controlled growth can take place under molecular beam epitaxy (MBE) conditions. We have performed optical spectroscopy at several different locations downstream of the nozzle for different tip polarity and different argon/nitrogen gas mixtures, characterizing the expansion as it unfolds. Overall nitrogen intensities range from the 5x10@super 17@-2x10@super 18@ molecules/sr/s. Our calculations indicate that an appreciable percentage (ca.10%) of the nitrogen molecules is in the desired metastable A@super 3@@SIGMA@@super +@@sub u@ state. Growth studies of AlN on Si(100) are currently under way. The low cost, the ease of operation and the ability to produce only a single excited species are in stark contrast to the broad spectrum of different species of any other commercially available plasma source, making the corona discharge source attractive for a broad range of future applications. Supported by ONR grant # N00014-95-1-0122 & N00014-96-1-0962 @FootnoteText@ @footnote 1@ R.P.Muller, B.L.Tsai and W.A.Goddard III, SEE-3 Workshop, Tempe 1998

4:20pm **SE-WeA8 Development of Atomic Nitrogen Sources and Atomic Nitridation Processes**, ***O. Gluschenkov,*** *K. Kim,* University of Illinois, Urbana-Champaign

With the goal of developing an efficient source of atomic nitrogen suitable for electronic materials processing, we have fabricated novel atomic nitrogen sources and with them conducted an investigation of nitrogen dissociation in a low-pressure nitrogen plasma. Plasma electric field, electron density, and vibrational temperature of nitrogen molecules have been estimated from experimental data obtained with the prototype sources. A simple model has been developed to predict the efficiency of atomic nitrogen production as a function of the source parameters: pressure, geometry, deposited power, and nitrogen throughput. An atomic nitrogen source with 60% of nitrogen atoms at the output has been constructed to study the atomic nitridation processes, the processes where nitridation is effected by atomic nitrogen only. The extremely high chemical potential of atomic nitrogen, small size of nitrogen atoms, and absence of other energetic particles and chemical contaminants lead to a dramatically different chemical kinetics and allow for high-rate, low-temperature, low-pressure, and low-damage processing. The processes investigated include the nitridation of thin SiO@sub 2@ gate dielectric and the growth of Group-III-Nitride crystals.

4:40pm **SE-WeA9 Energetic Oxygen Atom Surface Passivation of Cd@sub 1-x@Zn@sub x@Te Radiation Detectors**, ***M.A. Hoffbauer,*** *S. Cook, T. Prettyman, J. Rennie,* Los Alamos National Laboratory*; J.C. Gregory, M.A. George,* University of Alabama, Huntsville

Recent investigations show considerable progress in developing large-volume Cd@sub 1-x@Zn@sub x@Te radiation detectors for room-temperature x-ray and gamma-ray spectroscopy and imaging where bulk material with high resistivity and uniform electrical properties is required.@footnote 1@ Surface effects can also play an important role in the performance of CdZnTe spectrometers, since dark current may be dominated by surface leakage in gridded or pixellated devices.@footnote 2@ A novel surface oxidation process has been developed for the treatment of CdZnTe using a source of energetic oxygen atoms to treat the

surface held near ambient temperatures.@footnote 3@ Following the oxidation process the chemical composition and morphology of the surface were investigated using X-ray photoelectron spectroscopy and atomic force microscopy. No detectable unreacted Te substrate XPS feature is observed. The Te-oxide peak indicates that the oxidation process is complete, and that the suspected Te precipitates left on the surface following polishing and etching have been totally reacted to form a uniform Te-oxide layer >10 nm thick. AFM studies show a relatively uniform and smooth surface oxide layer. A significant reduction in surface leakage current and detector noise results in a 25% improvement in detector resolution measured at a gamma-ray energy of 662 keV. This new surface passivation method for high-quality, spectrometer-grade material increases the accuracy and sensitivity of measurements of radionuclides with complex gamma-ray spectra, including special nuclear material. When CdZnTe detectors with small spacing between electrodes become available, surface passivation will be even more critical in determining performance and energy resolution. @FootnoteText@ @footnote 1@K. B. Parnham, "Recent Progress in Cd@sub 1-x@Zn@sub x@Te Radiation Detectors," Nucl. Instr. Meth. Phys. Res., A377, 487(1996). @footnote 2@K.T.Chen, D.T. Shi, B. Granderson, M.A. George, W.E. Collins, A. Burger, and R.B. James, "Study of Oxidized Cadmium Zinc Telluride Surfaces," J. Vac. Sci. & Technol. A15, 850(1997). @footnote 3@M.A. Hoffbauer, J.C. Cross, and V.M. Bermudez, "Growth of Oxide Layers on Gallium Arsenide with a High Kinetic Energy Atomic Oxygen Beam", Appl. Phys. Lett., 2193(1990).

5:00pm **SE-WeA10 The Atmospheric-Pressure Plasma Jet: Properties and Materials Applications*, A. Schütze,*** University of California, Los Angeles*; J. Park,* Los Alamos National Laboratory*; S.E. Babayan, J.Y. Jeong, V.J. Tu,* University of California, Los Angeles*; G.S. Selwyn,* Los Alamos National Laboratory*; R.F. Hicks,* University of California, Los Angeles

Atmospheric-pressure plasma jets can be used in a wide range of materials applications, including surface cleaning, selective etching and thin-film deposition. The plasma source consists of two closely spaced electrodes through which helium and other gases flow (O@sub 2@, CF@sub 4@, etc.). A variety of electrode configurations can be used, and the source is suitable for large-area processing of materials. Measurements with an impedance probe have shown that this source exhibits a low breakdown voltage at atmospheric pressure, between 50 and 300 V, depending on the gap spacing and gas mixture. The current-voltage characteristics are analogous to a low-pressure DC discharge, in which normal and abnormal glow regions occur. Normal glow is observed between 0.01 and 1.0 A with a corresponding voltage of about 150 V. As an example application, we will discuss the plasma-assisted chemical vapor deposition of silicon dioxide. Film growth rates of 0.3 to 1.0 µm/min are achieved using tetraethoxysilane or silane sources. The growth rate increases linearly with RF power and Si source pressure, but decrease with increasing pressure. The properties of the SiO@sub 2@ films deposited at 350 °C, as determined by infrared spectroscopy, photoemission spectroscopy and capacitance measurements, are comparable to those of thermally grown SiO@sub 2@ films at 900 °C.

Selected Energy Epitaxy Topical Conference
Room 327 - Session SE-ThM

In Situ Characterization and Real-Time Diagnostics of Surface Growth Processes

Moderator: R.D. Tromp, IBM T.J. Watson Research Center

8:20am **SE-ThM1 Low Energy Electron Microscopy of SEED Growth of GaN Layers**, *A. Pavlovska,* ***E. Bauer,*** *I.S.T. Tsong, V.M. Torres, R.B. Doak,* Arizona State University **INVITED**

The early stages of growth of GaN layers on GaN(0001), 6H-SiC(0001) and on Si(111) surfaces are studied in a low enery electron microscope equipped with a NH@sub 3@ seeded He supersonic jet source, a RF discharge nitrogen source and a thermal NH@sub 3@ beam source. This allows a comparison of the influence of the different substrates and deposition modes on the growth and structure of the layers. Results will be reported on the effects of relative arrival rate of Ga and N containing species, of the substrate temperature and surface condition.

9:00am **SE-ThM3 Observation and Nucleation Control of Ge Growth on Si Surfaces using Scanning Reflection Electron Microscopy**, ***M. Ichikawa,*** Joint Research Center for Atom Technology, Japan **INVITED**

Scanning reflection electron microscopy (SREM) is one of the useful techniques for studying surface phenomena and also for modifying surfaces through the use of a focused beam. We have developed high-resolution SREMs (2 nm beam diameter) combined with other surface analysis techniques, such as STM, scanning Auger electron microscopy and X-ray photoelectron spectroscopy (XPS), and applied these to study and control surface reaction phenomena. In this study, we mainly show that focused electron beam (EB)-stimulated reactions in ultra-thin SiO@sub 2@ films on Si substrates, are useful for controlling Ge growth on Si surfaces. Ultra-thin Si oxide films less than 1 nm thickness are formed by heating clean Si substrates in oxygen gas at about 700 °C. The thermal oxidation occurs layer-by-layer. The interface between the oxide film and Si substrate becomes atomically abrupt. The oxide film is mainly composed of silicon dioxide (SiO@sub 2@), which is confirmed by XPS. When the samples are annealed at about 750 °C after focused EB irradiation on the SiO@sub 2@ films at room temperature, Si clean surfaces (open windows) are exposed in the oxide films on the substrates due to the EB-stimulated oxygen desorption and selective thermal decomposition of SiO@sub 2@ at the EB irradiated areas. The typical size of these open windows is about 10 nm. After the deposition of Ge on the sample with Si open windows and subsequent annealing, Ge island growth occurs only in the window areas by Ge diffusion from the surrounding areas during the thermal decomposition of SiO@sub 2@ where Ge reacts with SiO@sub 2@ producing volatile SiO and GeO gases. Ge islands with 10-20 nm size can be formed at given areas on the Ge wetting layer by this method. Other Si nanostructures can be also formed by the selective thermal reactions on the patterned ultra-thin SiO@sub 2@. This work is supported by NEDO.

9:40am **SE-ThM5 Wurtzite GaN Surface Structure Studied by Scanning Tunneling Microscopy and Total Energy Calculations**, ***A.R. Smith,*** *R.M. Feenstra, D.W. Greve, M.-S. Shin, M. Skowronski,* Carnegie Mellon University*; J. Neugebauer,* Fritz-Haber-Institut der MPG, Germany*; J.E. Northrup,* Xerox Palo Alto Research Center **INVITED**

Using scanning tunneling microscopy (STM) and electron diffraction, two new families of reconstructions have been identified on wurtzite GaN surfaces. First-principles theoretical calculations have yielded a number of novel structural models - many consisting of metallic Ga surface layers - for these reconstructions. The two families of reconstructions are those associated with the inequivalent (0001) and (000-1) surfaces, denoted as Ga-face and N-face respectively. Films are grown using molecular beam epitaxy with an RF plasma source to activate the N@sub 2@ molecules. The N-face results from nucleating the growth directly on sapphire, while the Ga face is prepared through homoepitaxial growth on an MOCVD-grown GaN/sapphire template. For either polarity, smooth growth occurs under Ga-rich growth conditions whereas N-rich growth leads to surface roughening. On the N-face, the least Ga-rich structure is the 1x1, composed of a single Ga monolayer (or adlayer) bonded to the ideal, N-terminated bilayer. Higher-order reconstructions on this face, 3x3, 6x6, and c(6x12), occur with increasing Ga coverage. On the Ga-face, the most Ga-rich structure is the pseudo-1x1, consisting of a double layer of Ga atoms in a fluid-like discommensurate structure on the surface. Removal of Ga atoms from the pseudo-1x1 results in the 6x4, 5x5, and 2x2, in order of decreasing Ga coverage. The 6x4 and 5x5 appear to be composed primarily of Ga adatoms. The 2x2, on the other hand, is formed through nitridation of the annealed surface or by growth under nearly N-rich conditions and therefore is consistent with a N adatom 2x2. @FootnoteText@ This work is supported by the Office of Naval Research under contract N00014-96-1-0214.

10:20am **SE-ThM7 Low-Energy Electron Microscopy of (0001) Surfaces of GaN Films@footnote 1,2@**, ***M.G. Lagally,*** University of Wisconsin, Madison **INVITED**

The ability to observe growth in real space and in real time at growth temperatures and manipulate growth conditions dynamically is essential to determine fundamental mechanisms of epitaxial growth, especially in complex systems. Only low-energy electron microscopy (LEEM) provides this capability. We have begun a program of LEEM investigations of the surfaces of GaN films prepared in several ways as a springboard to subsequent in-situ exploration of homoepitaxial growth. Surfaces of films grown by metal-organic vapor phase epitaxy (MOVPE), by halide vapor phase epitaxy (HVPE), and by lateral epitaxial overgrowth (LEO) using MOVPE are compared. Although a number of surface reconstructions have been observed, clean stoichiometric GaN(0001) surfaces are unreconstructed, and hence conventional dark-field imaging cannot provide information on terrace sizes and step heights, although steps themselves can be viewed with step-contrast imaging. We demonstrate that through use of multiple scattering we can view terraces and step heights and determine terrace size distributions. We compare surface morphologies of the above films. We have also demonstrated (so far only on SiGe/Si) that LEEM has potential for imaging 3D features. We have identified 3D epitaxial islands and have followed in real time their shape and size evolution during embedding by matrix material. We will describe initial LEEM measurements of Ga deposition on the above GaN surfaces as a start to homoepitaxial growth. Although none of this work as yet reflects selected-energy epitaxy, it will help to establish the baseline for understanding growth mechanisms that might be modified by selecting the energies of the depositing species. @FootnoteText@ @footnote 1@Research supported by ONR. @footnote 2@Work done in conjunction with J. Maxson, L. Zhang, T. Kuech, and P. Sutter.

11:00am **SE-ThM9 Defect-Driven Nucleation Kinetics of GaN Growth on Sapphire(0001)**, ***A.R. Woll,*** *J.D. Brock, R.L. Headrick, S. Kycia,* Cornell University

Real-time, x-ray scattering techniques using the Cornell High Energy Synchrotron Source have been used to study the kinetics of GaN nucleation and growth on sapphire (0001) by RF plasma-assisted MOMBE. The initial growth rate of GaN, measured by gallium fluorescence, is observed to be highly nonlinear. The time to form the first bilayer was the same for substrates from the same wafer, but increased from 10 to 30 seconds on substrates with decreasing surface defect density, as indicated by x-ray measurements of surface quality. This suggests that the initial nucleation of GaN is defect-driven, perhaps occurring at steps on the surface. This work is supported by NSF Grant Nos DMR--9632275 (MSC) and DMR--9311772 (CHESS).

11:20am **SE-ThM10 Site-Selective Reaction of Br@sub 2@ with the Second Layer Ga Atoms on the As-rich GaAs(001)-2x4 Surface**, *Y. Liu, A.J. Komrowski,* ***A.C. Kummel,*** University of California, San Diego **INVITED**

The top layer of the GaAs(001)-2x4 surface consists of rows of As-As dimers while the second layer has exposed Ga atoms between the arsenic rows. Using scanning tunneling microscopy (STM), we have observed that in the initial adsorption stage monoenergetic Br@sub 2@ molecules (0.89 eV) react exclusively with the second layer Ga atoms exposed in trenches or at defects on the As-rich GaAs(001)-2x4 surface. This gallium-selective chemisorption indicates that bromine molecules preferentially react with exposed atoms which have the least filled dangling bonds regardless of their layer. Both abstractive and dissociative chemisorption of Br@sub 2@ molecules are observed to be surface-site selective. The abstractive chemisorption of Br@sub 2@ molecules formed isolated gallium monobromides at As atomic vacancies, As-As dimer vacancies, and in trenches. However, the dissociative adsorption of Br@sub 2@ molecules forms paired gallium monobromdies at As-As dimer vacancies and in trenches. Dissociative adsorption of a Br@sub 2@ molecules in a trench is orientation-specific and results in two GaBr species on the opposites sides of the trench.

Selected Energy Epitaxy Topical Conference
Room 327 - Session SE-ThA

Seeded Supersonic Beam Epitaxial Growth

Moderator: R. Bickness-Tassius, Jet Propulsion Laboratory

2:00pm **SE-ThA1 Selected Energy Epitaxial Deposition of GaN and AlN on SiC(0001) Using Seeded Supersonic Free-Jets of NH@sub 3@ in Helium**, *V.M. Torres,* Arizona State University*; **R.B. Doak,*** Fulbright Senior Scholar, Ruhr-Universitaet-Bochum, Germany*; B.J. Wilkens, David J. Smith, I.S.T. Tsong,* Arizona State University **INVITED**

By expanding a gas mixture into vacuum through a supersonic nozzle, a heavy "seed" species in a light diluent can be aerodynamically accelerated to suprathermal translational energies, tunable by adjusting the mixture and temperature of the nozzle. Such "seeded" beams retain the high intensity, directionality, and narrow energy distribution characteristic of a supersonic free-jet. They thus offer promise in selectively promoting specific gas-surface reactions, a matter of much current interest in the growth of III-N semiconductor thin films. We report the use of 10% NH@sub 3@ in He seeded beams to grow GaN and AlN epitaxially on 6H-SiC(0001) and to grow GaN on AlN buffer layers deposited on SiC(0001). The substrate temperature was 800° C in all cases and the incident NH@sub 3@ translational energy was varied from 0.034 to 0.44 eV. Deposition was made with the beam incident at 0°, 30°, and 75° with respect to the surface normal. Ga was supplied from a simple evaporator and all growth was carried out under Ga-rich conditions. The thickness and morphology of the resulting films was characterized ex situ using RBS, Auger, TEM, and AFM. Of particular relevance to the growth of III-N compounds are the following results: (1) Selected energy epitaxial growth was observed, evidently via a direct reaction channel over a barrier of 0.3 ± 0.1 eV and mediated by the NH@sub 3@ translational energy. (2) A low energy reaction channel was also identified and ascribed to physisorption of the incoming NH@sub 3@ molecule followed by dissociative attachment of NH@sub x@ fragments. (3) Comparison of growth at 0° and 30° beam angles revealed total energy scaling, possibly due to rotational coupling of the above two reaction channels. (4) Deposition at grazing angle (75°) yielded faceting oriented towards the beam, indicating minimal mobility of the incident NH@sub 3@ and the attached NH@sub x@ fragments. The experimental evidence will be presented and the implications for III-N growth examined. Supported by ONR grant # N00014-95-1-0122

2:40pm **SE-ThA3 Homoepitaxial Growth of GaN Using Seeded Supersonic Molecular Beams*, H.H. Lamb,*** North Carolina State University **INVITED**

The optoelectronics applications of the Group III-nitrides have stimulated great interest in low-temperature epitaxial growth of GaN. As the quality of heteroepitaxial GaN films is limited by lattice mismatch between the film and typical substrates (e.g., sapphire and 6H-SiC), we have chosen to focus on homoepitaxial growth of epilayers on high-quality MOVPE-grown GaN substrates. Hyperthermal beams of neutral molecules (e.g., NH@sub 3@) are employed as alternatives to plasma and/or ion sources for low-temperature growth. Hyperthermal molecular beams with narrow energy distributions are generated by seeding heavy species in a supersonic expansion of a lighter gas (typically He or H@sub 2@). In this presentation, homoepitaxial growth of GaN using dual seeded supersonic molecular beams of NH@sub 3@ and triethylgallium (TEG) will be described. The results will be compared to those obtained using an NH@sub 3@-seeded supersonic molecular beam and a conventional Ga effusion cell. The influence of precursor kinetic energy on growth kinetics and film morphology will be discussed.

3:20pm **SE-ThA5 The Effect of Scaling Precursor Duty Cycles on Pulsed Supersonic Molecular Beam AlN Growth Rates*, V.W. Ballarotto,*** *M.E. Kordesch,* Ohio University

The effect of varying the precursor duty cycles for AlN grown on Si (100) at 650 °C with pulsed supersonic molecular beams is reported. The duty cycle is defined as the on-time of the valve multiplied by the driving frequency. The Al precursor was trimethylaluminum (130 meV) and the N precursor was 5 percent ammonia seeded in He (220 meV). The duty cycle was varied by changing the driving frequency. The growth rate of AlN films increases linearly (0.09 μ/h to 0.50 μ/h) with an increase in driving frequency. However, the growth rate in terms of thickness per pulse is roughly constant (1 Å/pulse). Total film thickness is on the order of 1-2 μ. A comparison of the growth rates when the duty cycle is varied by changing valve on-time will be presented. The films are predominantly oriented with the non-polar (10-0) plane parallel to the substrate plane. Preliminary results from x-ray diffraction @phi@ scans show that the films exhibit a preferred orientation that does not depend on substrate orientation or film thickness. The nucleation and growth of the non-polar (10-0) film face on polar (0001) MOCVD AlN will be discussed. Support provided by BMDO/ONR N00014-96-1-0782 and -1060.

3:40pm **SE-ThA6 In-Situ Surface Cleaning of GaN Using Hyperthermal Molecular Beams*, A. Michel,*** North Carolina State University, US*; E. Chen,* North Carolina State University*; O. Nam, D. Thomson, R.F. Davis,* North Carolina State University, US*; H.H. Lamb,* North Carolina State University

Selected energy epitaxy (SEE) of GaN on MOVPE-grown GaN/6H-SiC substrates requires in-situ surface cleaning techniques that are effective at removing carbon and oxygen contamination without roughening or otherwise damaging the surface. Remote hydrogen plasma cleaning has been used to remove contaminants from GaN substrates prior to RF plasma-assisted MBE growth; however, the effects of hydrogen plasma exposure on surface roughness and substrate electrical properties have not been reported.@footnote 1@ Nitrogen plasma exposure can destroy surface steps on GaN/6H-SiC substrates, as evidenced by in-situ low energy electron microscopy (LEEM).@footnote 2@ Energetic beams of neutral atoms and molecules provide an alternative to plasma sources for in-situ cleaning and subsequent growth. Hyperthermal molecular beams are generated by seeding heavy species (e.g., NH@sub 3@, Kr) in a supersonic expansion of a lighter gas (e.g., He, H@sub 2@). In this work, in-situ cleaning of MOVPE-grown GaN/AlN/6H-SiC substrates using hyperthermal molecular beams was investigated. Removal of surface carbon and oxygen contaminants was achieved by heating at 730°C under a hyperthermal NH@sub 3@ beam. Oxygen is removed primarily by thermal desorption; however, carbon removal occurs only under an NH@sub 3@ flux. We infer that adsorbed H atoms produced by NH@sub 3@ decomposition react with carbonaceous species on the GaN surface to produce volatile hydrocarbons. Ex-situ atomic force microscopy (AFM) indicates that atomically smooth surfaces with regular steps are produced by NH@sub 3@ beam cleaning. In on-going work, we are investigating the use of dual hyperthermal Kr and NH@sub 3@ beams for GaN cleaning. The effects of kinetic energy on surface contamination removal and surface morphology will be discussed. @FootnoteText@ @footnote 1@W.C. Hughes, W.H. Rowland, Jr., M.A.L. Johnson, S. Fujita, J.W. Cook, Jr., J. Ren, and J.A. Edmond, J. Vac. Sci. Tech. A, 13, 1571 (1995).@footnote 2@E. Bauer, private communication.

4:20pm **SE-ThA8 Controlling Thin Film Morphology and Selectivity using Collimated Monoenergetic Molecular Beams*, J.R. Engstrom,*** Cornell University **INVITED**

Over the past several years we have been investigating the fundamental aspects of thin film growth using energetic neutral molecular beams produced by supersonic expansions as sources. Our focus has been on Group IV systems-- Si, Ge and Si@sub 1-x@Ge@sub x@. This work has ranged from detailed investigations of the gas-surface chemical dynamics of dissociative adsorption, to thin film deposition and growth emphasizing morphological aspects, to computer simulations of both the thin film morphology and gas-surface fluid dynamics. We will present an overview of this work, focusing on more recent developments, which will include (i) the growth of thin films at grazing angles of incidence; (ii) the selectivity of growth (e.g., Si vs. SiO@sub 2@) as a function of beam energy, beam composition and substrate temperature; and (iii) the exploration of scale-up strategies (experiment and computer simulation) for deposition over large areas.

5:00pm **SE-ThA10 Three Dimensional Modeling of Silicon Deposition Process Scale-up Employing Supersonic Jets***, G. Chen,* ***I.D. Boyd,*** *J.R. Engstrom,* Cornell University

A new technique to deposit silicon thin films employing supersonic beams is examined. Our previous studies involved both experimental and numerical approaches, in which the thin films were deposited at high growth rates but over relative small areas. The current studies are focused on the process scale-up by using multiple discrete supersonic jets. 1% disilane/hydrogen mixture is heated to 350 °C and ejected through nozzles to a 700 °C substrate. Three dimensional simulations are conducted to investigate the geometrical effects of the molecular beam sources. One source configuration involving multiple jets is found to successfully deposit uniform silicon films over an area of 18 cm in diameter, with a growth rate higher than 200 @Ao@/min. The molecular beam energy obtained under these conditions is approximately 1.3eV. A configuration is also designed to

increase the deposition area in a laboratory facility for experimental verification.

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