

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 $\sim 1 \times 10^{13} \text{ cm}^{-2}$ with no intentional doping, due to the piezoelectric effect. The drain-source breakdown voltage at pinchoff rises linearly with gate length, being $> 200 \text{ V}$ for $1 \mu\text{m}$ gates due to the 3-4 MV/cm breakdown field strength. Using SiC substrates having $> 3 \text{ W/cm}^2 \text{ K}$ thermal conductivity, up to 20 W/mm periphery will be possible. The normalized drain current is $> 1 \text{ A/mm}$, yielding a high normalized optimum load of $\sim 200 \text{ ohm-mm}$ for $1 \mu\text{m}$ gates. Large periphery HEMT's with reasonable load resistances will allow power levels $> 100 \text{ W}$, with efficiency above 60%, for frequencies $< 12 \text{ GHz}$. The impact of dislocations, with density of $.5 - 2.0 \times 10^9 \text{ cm}^{-2}$ for GaN on SiC, on electron mobility has been determined analytically, and is in the range of 1,500-2,000 $\text{cm}^2/\text{V-s}$. 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 $2.7 \times 10^7 \text{ cm/s}$ and is reached at 150-200,000 V/cm. Short gate (.15 μm) HEMT's have unity current gain frequency of $\sim 70 \text{ GHz}$, and unity power gain frequency of 140 GHz. Due to the large bandgap, operation with channel temperatures $> 200^\circ\text{C}$ 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. Parkhomovskiy, 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 roughness 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 eV 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 photoluminescence. 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.

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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⁻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 mm² 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 performance¹. 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^{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 possess etch rates ranging from 8 nm/minute up to 160 nm/minute. The etches utilize one or more of the following fluorinated gases: NF₃⁴, SF₆⁶, CHF₃³, or CF₄⁴. A more detailed characterization of the etch recipes will be given in the full paper, and partial details have been reported elsewhere^{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. ¹J.B. Casady and R.W. Johnson, *Solid-St. Elect.*, Vol. 39, No. 10, p. 1409, 1996. ²P.H. Yih, V. Saxena, and A.J. Steckl, *Phys. Stat. Sol. (b)* Vol. 202, p. 605, 1997. ³G. 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 ⁴J.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. ⁵P.H. Yih and A.J. Steckl, *J. Electrochem. Soc.*, Vol. 140, p. 1813, 1993. ⁶J.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 oxycarbides¹, 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_x, x<2) and silicon oxycarbide (SiO_xC_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 a non-crystalline SiO₂ 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. ¹B. Hornetz, H-J. Michel, J. Halbritter, *J. Mater. Res* 9, 3088 (1994).

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