SYMPOSIUM E

Wide-Bandgap Electronics

April 17 – 20, 2001

Chairs

Thomas E. Kazior
Advanced Device Ctr
Raytheon RF Components
Andover, MA 01810
978-684-8586

Chanh Nguyen
Global Communications Semicond Inc
Torrance, CA 90505
310-530-7274

Primit Parikh
Cree Lighting Co
Goleta, CA 93117
805-968-9460 x216

Edward T. Yu
Electrical & Computer Engr Dept
Univ of California-San Diego
MC 0407
La Jolla, CA 92093-0407
858-534-6619

Symposium Support
†Cree, Inc.
Raytheon Company
SULA Technologies
†2001 Spring Exhibitor

Proceedings to be published online
(see *ONLINE PUBLICATIONS* at www.mrs.org)
as Volume 680E
of the Materials Research Society
Symposium Proceedings Series.

* Invited paper

SESSION E1: INSERTION OF WIDE BANDGAP ELECTRONICS INTO THE MARKETPLACE
Chair: Thomas E. Kazior
Tuesday Morning, April 17, 2001
Salon 1/2 (Marriott)

8:30 AM *E1.1
COMMERCIALIZATION OF THE SiC MESFET. John Palmour, Cree Inc., Durham, NC.

New core technologies for RF and microwave subsystems, which can reliably deliver higher power levels at competitive or lower costs, are key elements in the pursuit of this market. Because SiC is a wide bandgap material (3.0-3.3 eV) it can support very high breakdown fields of 3.0 MV/cm, typically six times higher than those of either Si or GaAs (0.5 MV/cm). As a consequence, SiC-based devices can support very high voltage operation and high RF voltage swings, making this technology well suited for high power operation. Furthermore, the outstanding thermal conductivity of SiC–typically seven times better than GaAs and three times better than Si–allows SiC-based devices to more efficiently remove waste heat, and to operate at a lower transistor temperature which improves device lifetimes and reliability. All of these characteristics come together to enable SiC MESFETs to exhibit RF power densities four to five times greater than GaAs FETs. These larger power densities permit the use of smaller die size to achieve a desired total power level, which offsets the higher cost of SiC substrates as compared to GaAs or Si substrates. SiC MESFETs typically run at much higher voltages than their Si and GaAs counterparts, with drain voltages ranging from 24 to 48 volts and gate voltages from 5 to 10 volts. The resulting devices show much higher output impedance than a competing GaAs MESFET or Si LDMOS device. One consequence is that much simpler matching circuitry is needed, in contrast to the requirements of relatively low impedance GaAs MESFET and Si LDMOS devices. A typical SiC MESFET running at 3.1 GHz under pulsed conditions achieves a gain of 10 dB and 42% PAE for a peak output power of 120 W. SiC transistors are no longer laboratory curiosities, with the first commercial SiC product now released. This device meets the full IS95 CDMA requirement for linearity when backed-off from the 1dB compressed power of typically 12 watts to 3 watts (a back-off of 6 dB compared to 9 dB for LDMOS). The device is also suitable for TDMA, GSM, EDGE and W-CDMA applications. 30 W and 60 W transistors are being developed. The 10 W production device delivers a power density of approximately 2 W/mm, although much higher values are possible. The latest experimental SiC MESFET results at 3.5 GHz exhibit an output power of 5.2 W/mm with 11.1 dB associated gain and 63% PAE; a power density six times higher than typically found for GaAs MESFETs.

9:00 AM *E1.2
AlGaN/GaN HEMT MICROWAVE POWER AMPLIFICATION. Lester F. Eastman, Electrical and Computer Engineering, Cornell University, Ithaca, NY.

High electron sheet density is polarization-induced with undoped AlGaN/GaN HEMT's on Ga-face GaN. Sheet resistance values in the range of 300-400 Ω/square are obtained with 250 Å Al.3Ga.7N barriers, and ohmic contact transfer resistances are .2-.3 Ω-mm. Using .20 μm footprint gates, ft values of 50-60 GHz and drain breakdown voltages of 45 V result. Si_3N_4 coating of the exposed AlGaN surface is used to stabilize the surface charge to minimize the DC-RF dispersion. Using SiC substrates, normalized CW power levels of 5-10 W/mm are obtained for small periphery devices, and 1 mm periphery devices have yielded 4-6 W/mm, up to Ku band. A monolithic integrated circuit, combining two HEMT structures, of one mm periphery each, has delivered 7.5 W maximum CW power at 40% power-added efficiency and has 2-8 GHz bandwidth. This latter M1MIC has a cascode configuration to yield enhanced gain and high power. Frequency and power scaling methods will be presented, showing expected high performance to 50 GHz. Research was supported under ONR MURI contract N00014-96-1-1223 monitored by Dr. John Zolper.

9:30 AM *E1.3
WIDE BANDGAP DEVICES: SYSTEM INSERTION REQUIREMENTS. Dave Laighton, Raytheon RF Components, Andover MA.

At present, solid state phased array systems are being exploited in a wide range of applications from radar applications to satellite communications systems. However, one of the primary limitations on these systems is the peak power that can be generated in a T/R module that fits within the element lattice spacing of such an array. To address this limitation a new class of microwave semiconductor power devices, based as wide bandgap semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN), offers significant promise. MMIC amplifiers based on these devices have the potential to produce as much as ten times more power per element than present GaAs MMIC power amplifiers. In addition, the much higher peak power available from wide bandgap devices allows the introduction of solid state replacements for transmitters that were formerly built with vacuum tubes. The prospects for these and for high power active apertures offer promise of low cost, reliable solid state transmitters for the future. GaN devices used for transmit MMICs can also be used for low noise amplifiers. Due to the inherent high breakdown voltage of GaN devices, such low noise devices may be able to operate reliably without limiter devices, which would significantly decrease system noise figure and further enhance system performance. While tremendous strides have been made in materials technology and device performance, a viable GaN MMIC technology is still 3-5 years away. Significant work still remains to be done in all areas of the technology including basic substrate growth (size and cost), epitaxial layer growth, device processing and device reliability. Perhaps the biggest single problem in realizing the promise of GaN is to be able to remove waste heat in GaN amplifier devices. This paper will discuss many of the systems needs and applications, as well as Raytheon's plan for developing the necessary technology to realize these applications in GaN.

SESSION E2: SUBSTRATES
Chair: Thomas E. Kazior
Tuesday Morning, April 17, 2001
Salon 1/2 (Marriott)

10:30 AM E2.1
SINGLE-CRYSTAL ALUMINUM NITRIDE SUBSTRATE PREPARATION FROM BULK CRYSTALS. Leo J. Schowalter[a], J. Carlos Rojo, and Glen A. Slack, Crystal IS, Inc., Latham, NY. [a] on sabbatical from the Physics, Applied Physics and Astronomy Dept., Rensselaer Polytechnic Institute, Troy, NY.

Aluminum nitride (AlN) has received attention as a candidate for III-nitride epitaxy applications due to its close lattice match, minimal differential thermal expansion compared to GaN, and high thermal conductivity. There is interest in AlN substrates as a competitive substrate for heteroepitaxial growth of GaN until commercial bulk GaN substrates become available. In addition, AlN is a more desirable substrate than GaN for device structures that require Al-rich nitride epitaxial layers such as solar-blind uv detectors and high power microwave devices. Since AlN is a very good electrical insulator, while having a higher thermal conductivity than GaN, it is also very desirable for high power switches. Large (15mm diameter and greater) AlN boules have been prepared using sublimation-recondensation growth. Currently, the best boules are approximately 70% single-crystal. We have demonstrated the possibility of preparing substrates, cut from these boules, for epitaxial growth using chemical-mechanical polishing (CMP) techniques, although significant differences between the different crystallographic orientations have been observed. High quality epitaxial growth of III-nitrides has been demonstrated on "a-face" substrates and on both the Al and the N face of "c-face" substrates. Recent x-ray topography of these substrates shows that the dislocation density averages less than 10^3 cm^{-2} in the substrates but also that the dislocations are not uniformly distributed. The thermal conductivity has been measured to be 2.85 W/K-cm. Cathodoluminescence of the AlN substrates indicates excellent band edge luminescence although deep level luminescence is observed and the level of the deep level luminescence appears to be correlated with the oxygen content (~500ppm) of the material. We will present current characterization of these substrates and of the epitaxial layers grown on them.

10:45 AM E2.2
ANALYSIS OF ELECTRON TRANSPORT IN A HIGH MOBILITY FREE-STANDING GaN SUBSTRATE GROWN BY HYDRIDE VAPOR PHASE EPITAXY. F. Yun, and H. Morkoc, Dept of Electrical Engineering and Physics, Virginia Commonwealth University, Richmond, VA; D.L. Rode, Washington University, Dept of Electrical Engineering, St. Louis, MO; K.T. Tsen, Dept of Physics, Arizona State University, Tempe, AZ; L. Farina and C. Kurdak, Physics Dept, University of Michigan, Ann Arbor, MI; S.S. Park, and K.Y. Lee, Samsung Advanced Institute of Technology, Suwon, KOREA.

Semiconductor nitrides have received a great deal of attention due to the demonstration of light emitters, light detectors, and high power amplifiers. Defects present, due in large part to a large lattice mismatch with the substrates used, prevent the potential of this material system from being attained. Among all the substrate options explored so far, free-standing GaN templates appear ideal for homoepitaxial growth of GaN films. To this end, hydride vapor-phase epitaxial grown GaN templates with a thickness of more than 200 μm were thermally lifted off from the sapphire substrate and mechanically polished. Transport properties were investigated by variable temperature Hall measurements on the Ga-face, both as-prepared and

with the N-face etched, in a temperature range of 25 to 350 K. For as-prepared GaN, Hall mobilities of 1100 cm^2/V-s and 6800 cm^2/V-s were obtained at room temperature and 50 K, respectively. For GaN with the N-face etched by about 15 μm, Hall mobilities improved to 1200 cm^2/V-s and 7600 cm^2/V-s at room temperature and 50 K, respectively. A numerical solution of the Boltzmann transport equation (BTE) that deals with the inelastic nature of electron scattering by polar optical mode was employed to determine the acceptor concentration. In order to combat errors introduced by scatter in the reported data, Raman spectroscopy was employed to obtain LO and TO phonon energies, which were then used in the above mentioned calculations. The best fittings of the mobility and carrier concentration data yield an acceptor concentration of $4.9x10^{15}$ cm^{-3} and a donor concentration of $2.10x10^{16}$ cm^{-3} for the as-prepared GaN. The acceptor concentration decreased to $3.0x10^{15}$ cm^{-3} after etching of the N-face, based on BTE iteration. Our analysis demonstrated high quality of the free-standing GaN substrate with the highest reported electron mobility for the wurtzite structure. Particulars of the sample preparation and measurements, and the BTE analysis will be discussed.

11:00 AM E2.3
CHARACTERIZATION OF VERY LOW DEFECT-DENSITY FREE-STANDING GaN SUBSTRATE GROWN BY HYDRIDE-VAPOR-PHASE EPITAXY. P. Visconti, Virginia Commonwealth University, Richmond, VA and Istituto per lo Studio di Nuovi Materiali per l'elettronica, CNR, Lecce, ITALY; M.A. Reshchikov, K.M. Jones, F. Yun, R. Cingolani, and H. Morkoc, Virginia Commonwealth University, Richmond, VA; S.S. Park, and K.Y. Lee, Samsung Advanced Institute of Technology, Suwon, KOREA.

Structural, electrical and optical properties of free-standing 200 μm thick GaN films grown by hydride vapor phase epitaxy (HVPE) have been investigated. After laser induced lift-off, the GaN substrates were mechanically polished on both Ga and N-sides and dry etched only on the Ga-side to obtain a smooth epi-ready surface. Hot H_3PO_4 chemical etching on both surfaces was used to reveal the defect sites which appeared as hexagonal pits. The etched surfaces were then examined by atomic force microscopy. A few seconds of etching was sufficient to smooth the surface and to produce etch pits with a density of $1x10^7$ cm^{-2} on the N-face. In contrast, a 50 minute etching was needed to delineate the defect sites on the Ga-face which led to a density as low as $5x10^5$ cm^{-2}. The full-width at half-maximum (FWHM) of the symmetric (0002) X-ray diffraction rocking curve was 69 and 160 arcsec for the Ga and N-faces, respectively. That for the asymmetric (104) peak was 103 and 140 arcsec for Ga and N-faces, respectively. Hall measurements demonstrated very high mobility (1100 and 6800 cm^2/Vsec at 295 and 50 K, respectively) and very low concentration of donors ($2.1x10^{16}$ cm^{-3}) and acceptors ($4.9x10^{15}$ cm^{-3}). In the photoluminescence (PL) spectrum taken at 10 K, a rich excitonic structure has been observed with the highest peak attributed to the exciton bound to neutral shallow donor (BDE). The FWHM of the BDE peak was about 1.0 meV on Ga face before and after hot chemical etching, whereas that on the N-face decreased from about 20 to 1.0 meV after chemical etching owing to the removal of the surface damage originated from the mechanical polishing. Instead of the omnipresent yellow luminescence, a green broad band with the maximum at about 2.4 eV has been observed which is attributed to deep acceptors.

11:15 AM E2.4
HIGH SPATIAL RESOLUTION THERMAL CONDUCTIVITY INVESTIGATION OF SiC WAFERS. D.I. Florescu, Fred H. Pollak, Physics Department and New York State Center for Advanced Technology in Ultrafast Photonic Materials and Applications, Brooklyn College of CUNY, Brooklyn, NY; G.R. Brandes, B.E. Landini, A.D. Salant, ATMI, Inc., Danbury, CT.

Silicon carbide (SiC) is a material with very attractive properties for high power/high temperature electronic devices. Its mechanical strength, high thermal conductivity (κ), large bandgap, and extreme chemical inertness are a few of the characteristics making SiC interesting for semiconductor electronics. Due to the significant heat load generated in large area, high power devices, it is desirable for the thermal properties of the substrate to be uniform and optimal. Scanning thermal microscopy (SThM), which provides nondestructive, absolute measurements of the thermal conductivity with a spatial/depth resolution of about 3 μ, was used to examine the room temperature thermal conductivity as a function of position for four 2" diameter SiC wafers. Wafers of 4H and 6H polytype were fabricated with carrier concentrations in the (1 - 3) x 10^{18} cm^{-3} and (6 - 9) x 10^{17} cm^{-3} ranges, respectively. A radial distribution of the thermal conductivity was determined for all the investigated samples. For a radius r < r1 (r1 $\sim$ 0.3") and r > r2 (r2 $\sim$ 0.7") highest thermal conductivity values were measured in the (3.8 - 3.9) W/cm-K range, comparable to the highest κ reported for this material [1-3]. For r1 < r < r2 the thermal conductivity drops to about (3.0 - 3.5) W/cm-K interval. The κ dip arises from a higher defect density in this region that may be associated with the edge of basal plane. Defect densities in the three regions will be presented. The implications of these findings for device application and design are considered. The ATMI and Brooklyn College work was supported in part by grant N00014-99-C-0160. 1 D. Morelli et. al, Inst. Phys. Conf. Ser. 137, 313 (1993). 2 E.A. Burgemeister et. al, J. Appl. Phys. 50, 5790 (1979). 3 See, for example, Proc. 1997 Int. Conference on SiC and Related Materials, Stockholm, Sweden.

11:30 AM E2.5
EXAMINATION OF BULK GaN CRYSTALS BY NONLINEAR OPTICAL ANALYSIS AND HIGH-RESOLUTION X-RAY DIFFRACTION IMAGING. N.A. Sanford, B. Steiner, National Institute of Standards and Technology, Boulder, CO.

A study of the structural and optical uniformity of bulk GaN single crystals was performed using nonlinear optical (NLO) analysis and high-resolution X-ray diffraction imaging. Polished and unpolished samples were examined that measured a few millimeters in cross-section and roughly 0.15 mm thick. NLO metrology is sensitive to both optical and structural features since the second-order susceptibility tensor depends critically on such factors as the symmetry of the crystal, the presence of mixed phases, and the presence of domains with reversed polarity. It is advantageous to correlate NLO results with detailed structural features revealed in full-crystal images recorded by X-ray diffraction imaging since NLO methods are conveniently adopted to the laboratory setting and can provide rapid feedback for crystal growth and sample processing. Subsurface damage induced in the samples by mechanical polishing was inferred by the variation in visibility of rotational Maker fringes for both o-polarized and e-polarized pump orientations. For the Maker fringe work, the pump beam was at a wavelength of 1064 nm and produced second-harmonic generation (SHG) in the samples at a wavelength of 532 nm. Additionally, the presence of mixed (cubic/hexagonal) structural phases was also suggested by the occurrence of extra o-polarized components in the SHG output. Subsurface damage was so prominent in the polished samples that it precluded X-ray diffraction imaging analysis of interior irregularities. Chemically assisted ion-beam etching of the polished faces to a depth of 200 nm failed to fully remove the subsurface damage. X-ray diffraction imaging performed on unpolished samples revealed a range of features including arrays of stacking faults and reversed domains. The reversed domains appear to be restricted to thin layers near the -c faces of the samples. Some of the stacking faults are associated with the -c face while other sets of faults travel obliquely through the crystal. One set of stacking faults is observed to traverse the thickness of the crystal in the c direction. Irregularities in the rotational Maker fringes corroborate the presence of domain-reversed layers in the unpolished samples. These irregularities resembled Maker fringe results taken from deliberately domain-inverted sections of lithium niobate and are manifested by extra fringes and split fringes. Ongoing work to be reported at the meeting includes reflected and transmitted SHG using a tunable pump source producing SHG in the samples that varies in the range from 360 nm to 425 nm which is in the vicinity of the absorption edge for cubic and hexagonal phases.

SESSION E3: EPITAXIAL GROWTH
Chair: Chanh Nguyen
Tuesday Afternoon, April 17, 2001
Salon 1/2 (Marriott)

1:30 PM *E3.1
InGaN CHANNEL FETS - GROWTH TECHNOLOGY AND CHARACTERISTICS. Erhard Kohn, I. Daumiller, M. Neuburger, Dept of Electron Devices and Circuits, M. Seyboth, C. Kirchner, Department of Optoelectronics, University of Ulm, Ulm, GERMANY; M. Kamp, Global Light Industries, Ulm, GERMANY.

GaN/InGaN-channel/GaN heterostructure FETs are attractive because of their (theoretically) high channel mobility, high velocity and high piezo-induced charge density. However, in case of the GaN/InGaN/GaN QW-structure both piezo-charges - electrons and holes - will reside in the well. This allows to remove the positive piezo-charge from the surface seen in the case of the AlGaN/GaN heterostructure, but needs a compensating mechanism for the holes in the InGaN QW. This can be obtained either by direct donor doping of the QW channel or modulation doping from the rear side. Both types of these novel structures have been grown by MOCVD and processed. However, the growth of InGaN QW channels with smooth interfaces becomes increasingly difficult with increasing In-content and thus the In-content was limited to 10%. Even then the channel mobility as determined by Hall measurements is in the order of 250 cm^2/Vs for both case of direct doping and modulation doping. At present it is therefore difficult to identify the charge transfer properties from the

back supply layer. Nevertheless, this low mobility in this initial phase of the technology, allows to simulate the expected device performance based on the present material quality using a standard 2D-simulator based on the drift diffusion transport model. Due to the high InGaN/GaN piezo-charge density in the channel even at 10% In-content a current handling capability of more than 1.5A/mm is predicted. In the case of the channel doped hole compensated HFET structure a current density of 250 mA/mm was obtained at Lg=0.25 μm and drain breakdown voltage of approx. 120V, resulting in an extracted RF power density of 2.5 W/mm. In the case of the hole compensated inverted HEMT structure the first experiment has resulted in a maximum drain current of 500 mA/mm at Lg=1.5μm and a maximum drain voltage of 40V. A prime motivation to develop this type of device, despite the difficulties of heterostructure growth, is the absence of piezocharges on the surface, which may introduce charge storage, lag and dispersion effects in their power characteristics. Thus already for the hole compensated channel doped structure the large signal characteristics have been measured using a 50 W termination from quasi-DC to 10 GHz and no disperion has been observed, which is a strong indication that indeed charge storage effects are avoided. Passivation of these devices is on the way.

2:00 PM E3.2
PREPARATION OF INN AND INN-BASED HETERO-STRUCTURES BY MOLECULAR BEAM EPITAXY. Hai Lu, William J. Schaff, Jeonghyun Hwang and Lester F. Eastman, Department of Electrical and Computer Engineering, Cornell University, Ithaca, NY.

InN is an important III-V compound semiconductor with many potential microelectronic and optoelectronic applications. It is expected to have higher peak-drift velocity and higher peak overshoot velocity than GaN, large breakdown electric field and acceptable band gap. [1] The significant lattice mismatch between InN and GaN or AlN can result in a large piezo-electric charge, which is very advantageous for HEMT applications. [2] In this study, we prepared epitaxial InN on (0001) sapphire with an AlN buffer layer by molecular beam epitaxy with a migration enhanced technique, which is composed of an alternative supply of pure In atoms and nitrogen plasma. A series of samples were grown with different substrate temperatures ranging from 360°C to 590°C. As grown films were characterized by X-ray diffraction, reflective high-energy electron diffraction, atomic-force microscopy and Hall measurements. The optimum growth temperature for InN was found to be between 450°C and 500°C. We also found that thicker AlN buffer layer is preferred for better quality InN epilayer. With increasing the thickness of AlN buffer layer, the electron Hall mobility of according InN nearly continuously increases while the carrier concentration decreases. The surface morphology is also improved this way. Hall mobility more than 900 cm^2/Vs with carrier concentration ~2e18 cm^{-3} at room temperature was achieved in this study. Various InN-based heterostructures with AlInN or AlN barrier were fabricated. X-ray diffraction study clearly shows the formation of heterojunctions. 2-dimensional electron gas resulted from piezo-electric effect was observed in CV measurements. Some results on Mg doping of InN and growth of AlInN will be discussed as well. This work is supported by ONR N00014-99-1-0936 monitored by John Zolper. [1] B.E. Foutz, S.K. O'Leary, M.S. Shur and L.F. Eastman, J. Appl. Phys. 85, 7727 (1999). [2] B.E. Foutz, O. Ambacher, M.J. Murphy, V. Tilak and L.F. Eastman, Phys. Stat. Sol. B216, 415 (1999).

2:15 PM E3.3
GaN AND AlGaN/GaN HEMT ON (111) SILICON SUBSTRATES. A. Alam, B. Schineller, M. Heuken and H. Juergensen, AIXTRON AG, Aachen, GERMANY; A. Dadgar and A. Krost, Otto-von- Guericke Universitaet Magdeburg, Fakultaet fuer Naturwissen- schaften, Magdeburg, GERMANY; H. Hardtdegen, N. Nastase, H. Bay, M. Kocan, R. Schmidt, P. Kordos and H. Lueth, Institute of Thin Film and Ion Technology (ISI), Forschungszentrum Juelich, Juelich, GERMANY; Michael Bremser, AIXTRON AG, Pasadena, CA.

The advantages of the silicon substrate for the growth of AlGaN/GaN high electron mobility transistors (HEMT) in comparison to sapphire or silicon carbide are for instance very low cost for the mass production and a much better thermal conductivity compared to sapphire substrate. The growth of GaN and AlGaN/GaN HEMT structures on 2 inch silicon substrates (111) orientation in an AIX 200 RF MOCVD system has been investigated in this work. To find the process window for the growth of nitrides on Si substrate the influence of the main parameters of the AlN-nucleation layer like nucleation time, crystallisation time, V/III ratio and reactor temperature have been studied. The parameters have been changed between 4 and 16 minutes, 1 and 10 minutes, 400 and 5000, 540 and 900C for nucleation time, crystallisation time, V/III ratio and reactor temperatures, respectively. A nucleation time of 11 minute a crystallisation time of 2 minute, and a V/III ratio of 1280 and a reactor temperature of 720°C have been found as the ideal parameters with respect to structure characteristic for the nucleation layer. The white light interferometry measurements of the layer thickness show a standard deviation (std dev) of about 4% for samples with thickness of 1.3 μm. Room temperature photoluminescence spectra show a full width at half maximum of approximately 4 nm at a peak wavelength of 363 nm and a very weak yellow luminescence at 550 nm at a laser power of 10 mW for the best GaN samples. Very flat surfaces (rms $\ll$ 1 nm) could be observed using atomic force microscopy for crack free undoped GaN as well as for GaN/AlGaN HEMT structures. Electrical and structural properties will be presented and correlated to the growth conditions

2:30 PM E3.4
MOCVD GROWTH OF GaN ON FLAT AND MISORIENTED A-PLANE SAPPHIRE SUBSTRATES. Takao Someya, Katsuyuki Hoshino and Yasuhiko Arakawa, Research Center for Advanced Science and Technology and Institute of Industrial Science, University of Tokyo, Tokyo, JAPAN.

Growth of GaN-related materials on (11$\bar{2}$0) A-plane sapphire substrates has attracted a wide attention, since A-plane sapphire wafers with diameter of 8 inches are already available commercially and mass-produced cheaply, which would lead to low-cost nitride-based electronic and optoelectronic devices. In this work, we have successfully grown high-quality GaN with smooth surface morphology on A-plane sapphire substrates by metal organic chemical vapor deposition (MOCVD). Surface morphology observed with optical microscopy and structural qualities characterized by x-ray diffraction (XRD) are found to be very sensitive to misorientation angles of A-plane sapphire substrates. The misorientation angles were changed systematically and the angle was optimized to be 0.25°-0.50°. GaN layers were grown on A-plane sapphire substrates in an atmospheric pressure two-flow MOCVD system with a horizontal quartz reactor under the condition that was optimized for the growth of GaN on (0001) C-plane sapphire substrate. Here A-plane sapphire substrate tilted toward (10$\bar{1}$0)-direction by various angles (0°, 0.25°, 0.50°, and 0.75°). The thickness of GaN layers was 2.3 μm. When the misorientation angle was 0.25°, the surface of GaN observed by optical microscopy was smooth without facet structures. In contrast, samples grown on a flat substrate and misoriented substrates with angle of 0.75° shows very rough surface morphology. The surface of the 0.50° sample was slightly rough in comparison with that of 0.25° sample, but much better than those of the 0° and 0.75° samples. These results are consistent with high-resolution XRD measurements: Peak linewidths of GaN in XRD rocking curves get minima (269 arcsec and 268 arcsec for 0.25° and 0.50° samples, respectively), while those are 304 arcsec and 282 arcsec for 0° and 0.75° samples, respectively. Furthermore, PL spectra were measured at room temperature for these four samples. All samples show similar spectral line shapes with very small yellow band emissions. PL intensities of 0.25° and 0.50° samples are by 20% and 40%, respectively, stronger than those of reference GaN on C-plane sapphires, encouraging for light-emitting device applications.

2:45 PM E3.5
ELECTRICAL PROPERTIES OF MBE GROWN Si-DOPED $Al_xGa_{1-x}N$ AS A FUNCTION OF NOMINAL Al MOLE FRACTION UP TO 0.5. M. Ahoujja, Y.K. Yeo, and R.L. Hengehold, Air Force Institute of Technology, Wright-Patterson AFB, OH; J.E. Van Nostrand, Air Force Research Laboratory, Wright-Patterson AFB, OH.

In recent years, considerable efforts have been made on the fabrication of various nitride based electronic and optoelectronic devices. However, there have been relatively few studies on the growth and properties of $Al_xGa_{1-x}N$ alloys, especially for $x > 0.3$. In the present work, the electrical properties of 1 μm thick, Si-doped ($\sim 10^{18}$ cm^{-3}) $Al_xGa_{1-x}N$ films grown on sapphire substrates with AlN buffer layers by gas source molecular beam epitaxy have been investigated as a function of Al mole fraction up to 0.5 using variable temperature Hall-effect measurements. The results of Hall measurements for $Al_xGa_{1-x}N$ with $x \leq 0.3$ show that the sheet carrier concentration remains constant up to 30 K, then decreases with temperature, reaching a minimum at 200 K, and finally increases exponentially with temperature up to 650 K. The constant carrier concentration at temperatures below 30 K is the evidence of a parallel conduction path near the interfacial region between the AlGaN and the sapphire substrate. Thus, a two conducting-layer model is used to extract the carrier concentration and mobility of the $Al_xGa_{1-x}N$ layer alone. For $Al_xGa_{1-x}N$ with $x \geq 0.4$, there are no measurable sheet carrier concentrations below 300 K, but they increase exponentially with temperature from 300 K to 650 K. For these $Al_xGa_{1-x}N$ samples with a nominal doping value of $1x10^{18}$ Si/cm^3, the measured room temperature carrier concentrations are $6x10^{18}$, $6.6x10^{18}$, $7.2x10^{18}$, $3.2x10^{18}$, $1.3x10^{18}$, and $6.8x10^{17}$ cm^{-3}, and the measured room temperature mobilities are 187, 74, 55, 14, 2, and 1 cm^2/Vs for x=0, 0.1, 0.2, 0.3, 0.4, and 0.5, respectively. These measured values will be compared with those of the $Al_xGa_{1-x}N$ layer alone. Also, it has been

determined that the activation energy of Si increases from about 10 to 70 meV as the Al mole fraction increases from 0 to 0.5.

3:30 PM E3.6
MOCVD GROWTH OF Ga(Al)N/InGaN/Ga(Al)N-HETERO-STRUCTURES: INFLUENCE OF THE BUFFER LAYER Al-CONCENTRATION AND GROWTH DURATION ON THE In-INCORPORATION IN InGaN. Marco Schowalter, Brigitte Neubauer, Andreas Rosenauer, Dagmar Gerthsen, Universität Karlsruhe, Laboratorium für Elektronenmikroskopie, Karlsruhe, GERMANY; O. Schön, A. Alan, Michael Heuken, AIXTRON AG, Aachen, GERMANY.

Transmission electron microscopy (TEM) was applied to study the structural properties of MOCVD-grown Ga(Al)N/InGaN/Ga(Al)N-heterostructures. The InGaN composition and In- distribution was determined quantitatively on an atomic scale by measuring the local lattice parameters from high-resolution TEM images with the evaluation program DALI (Digital Analysis of Lattice Images). Three samples with different Al-concentrations of 0, 19 and 36% in the buffer and cap layers were investigated. The strained InGaN quantum wells were always deposited under the same conditions. The measured average In-concentrations decrease with rising Al-concentration from 17 to 7 and 2.5% indicating that the increase of the lattice-parameter mismatch between the buffer and the InGaN significantly reduces the In-incorporation. In a series of GaN/InGaN/GaN-heterostructures, only the InGaN growth duration t_g was varied between 1 and 10 min under otherwise identical growth conditions. The average In-concentration was found to increase from 6 to 15% and the growth rate decreases with t_g as a consequence of the complex processes during the InGaN MOCVD growth. It has to be emphasized, that precise data on the InGaN layer thickness and composition, which is in particular necessary for the interpretation of photoluminescence spectra, requires the direct measurement in each sample. An inhomogeneous In-distribution was detected in all samples - even at a low average In-concentration of 2.5%. The composition inhomogeneities occur in two different dimensions: (a) In-agglomerates with sizes of only a few nanometers and In-concentrations significantly exceeding the average In-concentration and (b) fluctuations on the scale of a few 10 nm with smaller deviations from the average composition. While phase separation is the most likely origin of the larger scale fluctuations, random alloy fluctuations must be considered to be an alternative origin of the In-agglomerates.

3:45 PM E3.7
LAYER-BY-LAYER DEPOSITION OF GROUP-III NITRIDES BY TWO-STEP CYCLIC PROCESS. Svetoslav Koynov, Pedro Sanguino, Manfred Niehus, Reinhard Schwarz, Departamento de Fisica, Instituto Superior Tecnico, Lisbon, PORTUGAL; Ricardo Rocha, University of Aveiro, PORTUGAL; Helder Alves, Bruno K. Meyer, Justus-Liebieg-University, GERMANY.

Pulsed-Laser-Deposition (PLD) of group-III nitrides is an alternative of the conventional methods for preparation of these attractive large-band-gap materials. In contrast with the commonly used MO CVD, the PLD technique can prepare extremely pure films, which are free of carbon inclusions. On the other hand, the PLD films usually suffer from insufficient nitrogen incorporation and structural imperfection. The origin of these problems can be found in the contradictory requirements to the gas (plasma) atmosphere. It has to be an efficient nitrogen source (high reactivity, elevated pressure), but it also should permit transport of the laser-ablated species to the growing film (low pressure). We are preparing AlN and GaN films by applying a two-step cyclic process, which is intended to avoid the mentioned problems: - During the first step, an ultra-thin layer of nitrogen-poor material is deposited by PLD. A Nd:YAG laser (1064 nm) is used to ablate a target of pure Ga (Al). The rest atmosphere of N2 is kept at pressure as low as 10^{-4} mbar. - During the second step, additional nitrogen is incorporated into the last deposited layer by sustaining an intensive glow discharge in pure N2 at pressure as high as 1 mbar. The duration of this step controls the N-incorporation in the film. It also has a favourable effect on the film structure as the atoms in the ultra-thin layer preserve their mobility. The cycle of two steps is repeated until thick enough film is obtained (layer-by-layer deposition). Two kinds of AlN and GaN samples are studied - hetero-epitaxial films on sapphire substrates, deposited in the temperature range 600-800°C and polycrystalline films on quartz and Si substrates at lower temperatures. The effect of the N-content of the films is also investigated by depositing series of samples at different duration of the second step. X-ray diffraction, optical transmission spectra, PL spectra, Hall effect and conductivity measurements, as well as photoconductivity measurements are used to characterize the deposited samples.

4:00 PM E3.8
STRUCTURAL, OPTICAL AND ELECTRICAL PROPERTIES OF GaN FILMS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION ON SAPPHIRE. P. Visconti, Virginia Commonwealth University, Richmond, VA and Istituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY; M.A. Reshchikov, F. Yun, K.M. Jones and H. Morkoc, Virginia Commonwealth University, Richmond, VA; A. Passaseo, E. Piscopiello, A. Pomarico, and R. Cingolani, Istituto Nazionale di Fisica della Materia, Unita di Lecce and Dipartimento di Ingegneria dell'Innovazione, Universita' di Lecce, Lecce, ITALY; M. Lomascolo, M. Catalano, Istituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY.

Properties of GaN layers grown by metalorganic chemical vapor deposition (MOCVD) on c-plane of sapphire have been investigated using atomic force microscopy (AFM), wet etching for defect investigation, transmission electron microscopy (TEM), high-resolution X-ray diffraction, low-temperature photoluminescence (PL) and Hall effect measurements. Tapping-mode AFM images of the as-grown samples showed atomically smooth surfaces (rms roughness $\approx$ 0.2 nm) consisting of terraces separated by $\approx$ 3Å high bi-layer steps. Hot H_3PO_4 chemical etching was used to produce hexagonal-shaped etch pits at the surface defect sites as revealed by AFM imaging. The obtained etch pit densities (8-9x10^8 cm^{-2}) were in agreement with the dislocation density found by plan-view and cross-sectional TEM observations of the as-grown and H_3PO_4-etched samples. The full-width at half-maximum (FWHM) of the X-ray diffraction rocking curve was $\approx$ 4.8 and 3.9 arcmin for the symmetric (002) and asymmetric (104) directions, respectively. PL spectrum at 10 K demonstrated sharp peaks (FWHM $\approx$ 4 meV) in the excitonic region, which were attributed to free and bound excitons. The spectrum contained also weak PL bands with maxima at about 2.2, 2.9 and 3.27 eV, which have been attributed to three different acceptors.

4:15 PM E3.9
REDUCTION OF INCORPORATION OF B, Al, Ti AND N IN 4H-SiC EPITAXIAL LAYER GROWN BY CHEMICAL VAPOR DEPOSITION AT HIGHER GROWTH TEMPERATURE. Mitsuhiro Kushibe, Koh Masahara, Kazutoshi Kojima, Toshiyuki Ohno, Yuki Ishida, Tetsuo Takahashi, Takaya Suzuki, Sadafumi Yoshida, Kazuo Arai, Johji Nishio, Ultra-Low-Loss Power Device Technology Research Body, Tsukuba, JAPAN.

Dominant impurities in 4H-SiC epitaxial layer are considered to have origins in graphite susceptor. To reduce the concentration of impurities in epitaxial layer graphite susceptor is usually coated with SiC layer. When growth temperature is higher than 1600°C, however, sublimation rate of SiC increases rapidly and lifetime of SiC coating layer becomes shorter. This degradation of coating layer curtails adopting higher growth temperature though higher growth temperature is preferable to attain higher growth rate. In this work, reduction of impurity concentration of N, B, Ti and Al in epitaxial layer is pursued focusing on the effect of the growth temperature and the purity of graphite susceptor targeting at attaining purer epitaxial layer at higher growth temperature. Major impurities observed in the graphite were N and B. Dominant impurity in epitaxial layer were also N and B. SIMS revealed the existence of Ti in addition to them. When epitaxial layer was deposited at higher temperature, N concentration was higher as expected. On the contrary, concentration of B and Ti was lower when growth temperature was higher. By adopting higher growth rate, concentration of B and Ti was increased. These results suggest that concentration of B and Ti is higher on the surface of the epitaxial layer than inside of it and incorporation rate of B and Ti is reduced at higher growth temperature. Concentration of Al was also decreased with increasing growth temperature and Al was not observed when growth temperature was higher than 1500°C. Higher growth temperature is suggested to be preferable to obtain an epitaxial layer with lower concentration of B, Ti and Al though emission of them from graphite susceptor is considered to be serious. In addition, reduction of N concentration in graphite is suggested to be important to obtain purer epitaxial layer at higher growth temperature.

4:30 PM E3.10
INFLUENCE OF GROWTH PARAMETERS ON THE NITROGEN INCORPORATION IN 4H- AND 6H-SiC EPILAYERS GROWN BY HOT-WALL CHEMICAL VAPOUR DEPOSITION. U. Forsberg[a], M.K. Linnarsson[b], A. Henry[a], Ö. Danielsson[a], and E. Janzén[a]; [a]Dept of Physics and Measurement Technology, Linköping University, SWEDEN; [b]Solid State Electronics, Royal Institute of Technology, Stockholm, SWEDEN.

The hot-wall SiC CVD reactor was developed in our group several years ago to be able to grow thick low-doped epitaxial layers with good morphology for power devices. The hot-wall concept has got an increase in interest during the last years, however, no investigation of nitrogen incorporation in epitaxial SiC material has yet been presented.
The aim of this work is to study how the doping incorporation in epitaxial 4H-, 6H-SiC and on Si- and C face respectively depends on

the different growth parameters as temperature, pressure, C/Si ratio and growthrate. This work is related to our effort in growing MESFET structures, combined of a highly doped cap layer, medium doped channel layer and abrupt interfaces.
In each growth run, one sample of each above-mentioned polytype and face, i.e. a total of four samples, was used. The temperature was varied between 1500-1600°C, the pressure from 50-1013 mbar, the C/Si ratio from 1.5-5.0 and the growth rate from 1.5-6 μm/h. All growth runs were performed with intentional nitrogen doping to obtain a doping higher than 5×10^{16} cm^{-3}, necessary for the characterization using Secondary Ion Mass Spectrometry (SIMS). We will present doping incorporation dependence of different process parameters. Some results show that there is a difference between a cold-wall and a hot-wall reactor. Our results show that a temperature change of 75 degrees does not inflict the nitrogen doping on Si-face materials where as the nitrogen doping increases with decreasing temperature on C-face material. Change from "normal" process parameters may be necessary to obtain the high doping demanded for cap-layer, $> 2 \times 10^{19}$ cm^{-3}. Other observations reveal that there are similarities between previous reported results on doping incorporation in cold-wall reactor. A discussion based on "site competition epitaxy" and gas phase nucleation will be presented as an explanation of our results.

4:45 PM E3.11
GROWTH OF 3C-SiC LAYERS ON SILICON SUBSTRATES WITH A NOVEL STRESS RELAXATION STRUCTURE. Yoshihiro Irokawa, Noboru Yamada, Masahito Kodama, Tetsu Kachi, Toyota Central R&D Labs., Inc., Aichi, JAPAN.

Silicon carbide (SiC) has long been of interest for potential technological application, such as power devices and sensors, as one of the wide band gap semiconductors. The 4H and 6H type SiC wafers are supplied commercially. However, their high cost and the difficulty in obtaining large area are problems for their commercial use. The heteroepitaxially grown 3C-SiC layers on silicon (Si) substrates may make it possible to obtain larger area SiC at low cost and realize the combined devices of Si and SiC. Because of a 20% mismatch in the lattice constants of Si and 3C-SiC and an 8% mismatch in the thermal expansion coefficient, however, the resulting 3C-SiC films were not of device grade quality. To overcome these mismatches, Si substrates having cavities just beneath the surface layer were used. Trenches were made on Si(100) substrates by the photolithography and reactive ion etching (RIE). The depth of trench is 3.0μm and the radius of it is 0.4μm. The Si substrates with trenches were annealed in a hydrogen ambient in 10 Torr at 1300°C for 60 minutes. Trenches were transformed to cavities through the annealing process. Single crystalline 3C-SiC layers were grown on these Si substrates by means of low pressure chemical vapor deposition (LPCVD). The layers' quality was characterized by the cross-sectional TEM observations and the Micro-Raman spectroscopy. The TEM results showed that this structure reduced the defect density in the 3C-SiC layers. The averaged full width at half-maximum (FWHM) of LO Raman mode in 3C-SiC on these Si substrates became narrower than that on conventional Si substrates. These results suggest that these Si substrates are effective to relax the stress in heteroepitaxial growth of 3C-SiC.

SESSION E4: CHARACTERIZATION OF NITRIDES
Chair: Edward T. Yu
Wednesday Morning, April 18, 2001
Salon 1/2 (Marriott)

8:30 AM *E4.1
POLARIZATION-INDUCED ENERGY BARRIERS IN ELECTRONIC DEVICES. P. Asbeck, E. Yu, S.S. Lau, L. Jia, D. Keogh, D. Qiao, E. Miller, University of California, San Diego, CA; P. Miraglia, A. Roskowski, R.F. Davis, North Carolina State University, NC.

Bound charges associated with differences in polarization between different nitride materials, if not compensated with free charges, create strong electric fields, and associated potential drops. These potential drops can provide energy barriers to electrons or holes, which add to the energy barriers due to conduction and valence band offsets between the different materials. While in conventional III-V systems (for example, AlGaAs/GaAs or InP/InGaAs) 'bandgap engineering' is done solely on the basis of the band offset energies, with the nitride semiconductors, the polarization-based potentials can dominate the energy barrier formation. This leads to a modified design strategy for a variety of electronic devices. In this presentation, a simple formalism is provided to describe the energy barriers between different nitride semiconductors, taking into account both polarization and band-offset contributions. The formalism is applied to the formation of energy barriers in a variety of semiconductor devices of interest. These include: 1) Modification of the Schottky barrier height in an HFET. 'Camel diode' structures in which the effective barrier height is increased can be produced in straightforward fashion. 2) Modification of the surface potential in an ohmic contact. Designs can be used to provide an effective reduction of barrier height or thinning of the effective barrier. 3) Establishment of energy barriers for Hot Electron Transistors. These devices employ narrow potential wells filled with electrons to form the base of the n-n-n transistors. The polarization-based barriers allow tailoring the band structure over a wide range of energies and widths. 4) Establishment of energy barriers between channel layers and buffer layers of HFET structures. These structures can reduce penetration of carriers from the channel into buffer layers, in order to reduce trapping effects, decrease short channel effects and improve subthreshold behavior. Designs and supporting experimental results, on the basis of C-V and I-V measurements, using GaN/AlGaN and GaN/InGaN will be shown.
*Funding for this work has been provided by ONR and OSD under the MURI programs Polarization and Interfacial Effects in Semiconductors (POLARIS), and Compact Power Supplies Based on Wide Bandgap Semiconductors.

9:00 AM E4.2
SURFACE PHOTOVOLTAGE SPECTROSCOPY CHARACTERIZATION OF MULTIPLE QUANTUM WELL InGaN/GaN LIGHT EMITTING DIODES. B. Mishori, M. Muñoz, L. Mourokh, Fred H. Pollak, Brooklyn College of CUNY, Brooklyn, NY; J-P Debray, S. Ting, I. Ferguson, EMCORE Corporation, Somerset, NJ.

InGaN/GaN multiple quantum well (MQW) structures have attracted a lot of interest due to their importance in fabrication of blue-green light emitting diodes and laser diodes. Due to deep acceptor states, the p-dopant activation in the contact layer is crucial for device performance. Therefore, it is highly desirable to have a non-destructive method to monitor this property. The optical technique of surface photovoltage spectroscopy (SPS) can be used for this purpose. SPS measures the change in the contact potential difference between the semiconductor surface and a reference probe as a function of photon energy. The SPS signal is caused by photon absorption and charge carrier separation in the bulk, at structure interfaces and at the outer surface of the structure. The characterization of three InGaN/GaN MQW structures with different levels of p-type doping in the contact layer is presented. The SPS line-shape is governed by the contribution from two interfaces, i. e., the MQW active region/GaN contact layer and the surface space charge region of the GaN contact layer. The SPS signal from the MQW region shows a monotonic decrease with decreasing p-doping level in the GaN contact layer. This phenomenon is consistent with reduction of the electric field in the MQW region. Numerical simulation shows that high p-doping level of GaN contact layer screens the surface charge and increases the electric field at the MQW active layer/contact layer interface enhancing the SPS signal from this section. Simulation also demonstrates the high sensitivity of SPS spectrum line shape to p-doping level, suggesting this technique as a quality control tool.

9:15 AM E4.3
INFLUENCE OF THE DIPOLE INTERACTION ENERGY ON CLUSTERING IN InGaN. Eric J. Miller, Edward T. Yu, University of California-San Diego, Dept of Electrical and Computer Engineering, La Jolla, CA.

Compositional inhomogeneities in quantum-well heterostructures can have a dramatic effect on optical device properties by influencing the localization and emission wavelength of carriers. In InGaN/GaN quantum-well structures, it has been postulated that regions of In-rich material can significantly increase the recombination efficiency in blue/green light-emitting diodes and lasers, but the physical mechanism that would give rise to such clustering is not clear. In this work, we have performed analytical calculations and numerical simulations of the energy arising from interactions between the localized dipole moments that exist in each unit cell of an InGaN alloy to investigate the possible influence of this energy on compositional clustering. Electrostatic dipole interaction energy calculations have shown that the most energetically favorable configurations are those in which a unit cell containing an In atom has In atoms within the unit cells directly above and below it up to three unit cells away along the [0001] growth direction. This observation suggests that vertical In clustering is favored by this mechanism. It was also determined that anti-clustering perpendicular to the growth direction would be favorable, but to a lesser extent. By exchanging an In atom for a Ga atom in one of the three positions above or below an In atom, the dipole interaction energy is lowered by approximately 50 meV for $In_{0.20}Ga_{0.80}N$. This energy is similar in magnitude to the strain energy per unit cell in a pseudomorphically grown InGaN layer of the same composition.

9:30 AM E4.4
MEASUREMENTS OF SURFACE POTENTIAL ON GaN AND

$Al_{0.35}Ga_{0.65}N$/GaN HETEROSTRUCTURES BY SCANNING KELVIN PROBE MICROSCOPY. G. Koley and M.G. Spencer Department of Electrical and Computer Engineering, Cornell University, Ithaca, NY.

Scanning Kelvin Probe Microscopy (SKPM) technique operated in feedback mode is used to characterize GaN (n doped, n doped and semi-insulating), and $Al_{0.35}Ga_{0.65}N$/GaN heterostructures (with varying $Al_{0.35}Ga_{0.65}N$ thickness) grown by Metal Organic Chemical Vapor Deposition (MOCVD) and Molecular Beam Epitaxy (MBE). Both Ga-face and N-face samples have been investigated. The bare surface barrier height (BSBH) of these materials are measured with SKPM. The measurement technique is calibrated using metal calibration samples of Pt, Au, Ni and Al. The BSBH for n-doped GaN was measured to be 0.7 eV, which is in good agreement with values inferred from schottky barrier heights reported in the literature. Growth features such as dislocations present on the surfaces of III-nitrides are also investigated for their electrical properties using SKPM and non-contact mode Atomic Force Microscopy simultaneously. Dislocations appear negatively charged in both GaN and $Al_{0.35}Ga_{0.65}N$/GaN heterostructures. Detailed results will be presented.

9:45 AM E4.5
ELECTRON AFFINITY OF $Al_xGa_{1-x}N\{0001\}$ SURFACES OVER THE WHOLE COMPOSITION RANGE. H. Nienhaus, M. Schneider, S.P. Grabowski, W. Mönch, Laboratorium für Festkörperphysik, Gerhard-Mercator-Universität Duisburg, Duisburg, GERMANY.

Thin AlGaN layers with high Al-content have been proposed as an attractive material for cold cathode electron emitters if their surfaces exhibit true negative electron affinities (NEA). For long, it has been speculative if NEA occurs at such surfaces due to the sparse data base. In the present investigation, the electronic properties and the electron affinities of $Al_xGa_{1-x}N\{0001\}$ surfaces were studied by ultraviolet photoemission spectroscopy (UPS) over the whole composition range. The samples were prepared by N-ion sputtering and annealing. Surface cleanliness and stoichiometry were monitored with x-ray photoemission spectroscopy (XPS). The amount of residual oxygen was found to depend on the composition. Samples with high aluminum content showed traces of oxygen which could not be removed by further cleaning cycles. The results indicate that oxygen originates from the bulk and was obviously incorporated during the growth process. From UP-spectra the ionization energies and electron affinities as a function of composition x were determined. A decrease in electron affinity with increasing aluminum content was found, but the electron affinity remains positive for all x. Thus, earlier predictions of negative electron affinity for high aluminum content were not confirmed. Furthermore, oxidation experiments were carried out for $Al_{0.55}Ga_{0.45}N$ and AlN. The oxygen uptake and the influence of oxygen on the electron affinities were determined via XPS and UPS, respectively.

10:30 AM E4.6
HOLE SCATTERING IN P-TYPE WURTZITE GALLIUM NITRIDE. J.D. Albrecht, Naval Research Laboratory, Washington, DC; P.P. Ruden, University of Minnesota, Minneapolis, MN.

We investigate scattering processes for holes in wurtzite GaN using a six band Rashba-Sheka-Pikus Hamiltonian. Numerically integrated scattering rates for acoustic deformation potential, piezolectric acoustic phonon, polar optical phonon, and impurity scattering are calculated. We include the angular dispersion of the optical and acoustic phonon modes using continuum models. Both intra- and inter-band processes are examined taking into account the incomplete overlap of initial and final valence band states. The anisotropy of these scattering processes is analyzed for transport conditions that are dominantly parallel to, or perpendicular to, the hexagonal crystal axis, which usually coincides with the growth direction in GaN epitaxy. Both of these directions are relevant to currents in standard materials characterization experiments (such as Hall effect) and to device currents. In strained GaN, the anisotropic nature of the valence bands gives rise to considerable variations in the hole transport properties. The effects of biaxial and uniaxial strain on the valence bands involve a rich variety of phenomena that directly impact device design. Because both bandstructure and piezoelectric effects are involved, characterization experiments need to be supplemented by detailed analysis. By introducing a strain Hamiltonian description of the valence bands, our analysis is extended to calculate the changes in scattering probability due to pseudomorphic growth or external stress. Strain conditions are identified that can be used to exploit the strong in-plane directional dependence of the interband transfer processes which could lead to prefertially enhanced mobilities.

10:45 AM E4.7
STRESS EFFECTS IN p-TYPE AlGaN/GaN HETERO-STRUCTURES. Agustinus Sutandi, P. Paul Ruden, Univ of Minnesota, Dept of Electrical and Computer Engineering, Minneapolis, MN; Kevin F. Brennan, Georgia Tech, School of Electrical and Computer Engineering, Atlanta, GA.

The physics of bulk, wurtzite-structure III-nitride materials and of III-nitride heterostructures includes many phenomena that involve the modulation of their properties by externally applied stress. In particular, p-type material is expected to display a rich variety of piezo-resistive and piezo-optic effects that originate from the stress-induced modulation of lattice polarization charges, of valence band energies, and of bulk, surface, and interface defect states in the band gap. This discussion will focus on the expected effects of in-plane uniaxial and biaxial stress, and of hydrostatic pressure, on the quasi-two-dimensional hole gas at the interface of AlGaN/GaN heterostructures grown parallel to the hexagonal axis on sapphire substrates. The valence subband structure in the channel region is calculated self-consistently in the framework of a six-band Rashba-Sheka-Pikus (RSP) Hamiltonian. Stress-effects are included (in linear elastic theory) through deformation potentials and through the modulation of interfacial polarization charges associated with the piezoelectric nature of the constituent materials. We find that the charge carrier distribution is quite sensitive to the applied stress. Uniaxial stress leads to considerable anisotropy in the in-plane hole dispersion. This anisotropy will manifest itself in a variation of the channel conductance with respect to the stress axis.

11:00 AM E4.8
CHARACTERIZATION OF INVERSION DOMAINS IN GaN BY WET CHEMICAL ETCHING AND ELECTRIC FORCE MICROSCOPY. K.M. Jones, A.A. Baski, and H. Morkoc, Virginia Commonwealth University, Richmond, VA; P. Visconti, Virginia Commonwealth University, Richmond, VA, and Istituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY; A. Passaseo, E. Piscopiello and R. Cingolani, Istituto Nazionale di Fisica della Materia, Unita di Lecce and Dipartimento di Ingegneria dell Innovazione, Universita di Lecce, Lecce, ITALY; M. Catalano, Istituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY.

The existence of inversion domains in III-Nitride semiconductors degrades the performance of devices constructed with these materials. Consequently, it is imperative that we understand their electrostatic manifestation and the growth conditions under which domains form. In what is nominally referred to as Ga-polarity samples, N-polarity domains have a polarization that is reversed with respect to the rest of the surface, and will therefore stand at a different potential. Surface-contact-potential-electric-force-microscopy (SCP-EFM) is an extension of atomic force microscopy (AFM) that allows the imaging of the electrostatic potential on the surface. Employing a control sample with side by side Ga- and N-polarity regions, the particular mode of operation needed for EFM to determine the inversion domains was established. Using SCP-EFM, we have studied the inversion domains in GaN films grown by molecular beam epitaxy and metalorganic chemical vapor deposition, with a resolution of < 100 nm, by mapping the potential on the surface. Additionally, we have found that hot H_3PO_4 selectively etches N-polarity regions and extended defect sites at an extremely fast rate ($>$100 nm/min) resulting in very large and small etch pits, respectively. After etching, the areas with N-polarity can be distinguished from defect sites and the non-defective Ga-face surface by AFM imaging. The results of the SCP-EFM and wet chemical etching will be reported along with a comparison with plan-view transmission electron microscopy observations.

11:15 AM E4.9
INFLUENCE OF SPONTANEOUS AND PIEZOELECTRIC POLARIZATIONS ON THE LATTICE DYNAMICS OF III-NITRIDES STRUCTURES. Jérôme Gleize, Jean Frandon, Marie A. Renucci, L.P.S.T., CNRS, Université P. Sabatier, Toulouse, FRANCE; Friedhelm Bechstedt, I.F.T.O., F. Schiller Universität, Jena, GERMANY.

The influence of pyroelectric and piezoelectric polarizations on the lattice dynamics of strained III-nitrides structures is investigated within a macroscopic framework. New relationships between stress and strain are derived, which differ from Hooke's law. Consequently, the strained phonon frequencies in such systems might differ from those calculated within the elasticity theory framework. This is an important issue, for instance, in the calculation of the electron-phonon interaction in III-nitrides devices. In the case of highly strained AlN layers, grown along the [0001] axis on a lattice-mismatched substrate, a significant change in the strain along the growth direction is predicted. This results in a significant shift of the zone center phonon frequencies of bulk AlN. For strained GaN/AlN superlattices grown along the [0001] axis, the difference of the spontaneous polarizations of GaN and AlN also contributes to the change in the effective strain along the growth direction, which is due

to the presence of GaN/AlN interfaces in the structure. The corresponding shift of the zone center phonon frequencies of GaN and AlN might be negligible or significant, depending on the value of the ratio of the thickness of the GaN and AlN layers.

11:30 AM E4.10
PERSISTENT PHOTOCURRENT EFFECTS IN GaN/AlGaN MULTIQUANTUM WELLS. Annalisa Bonfiglio, Dipartimento di Ingegneria Elettrica ed Elettronica, Universita di Cagliari, ITALY; Giampiero Traetta, Mauro Lomascolo, Adriana Passaseo, Roberto Cingolati, Dipartimento di Ingegneria dell'Innovazione, Universita di Lecce, ITALY.

The transport of GaN and GaN/AlGaN heterostructures is attracting increasing interest due to the potential application of these materials to solar blind photodetectors and high mobility transistors. However the understanding of charge transport in these heterostructures is still quite poor. Systematic PhotoCurrent (PC) experiments on GaN/AlGaN multiple quantum wells, both spectrally and temporally resolved have shown that a photopersistence effect is present which can be traced back to a Yellow-Band-like feature which is not seen in PL, indicating the existence of defects which give rise to carrier trapping rather than recombination. A similar effect has already been observed in bulk GaN, but our observations support a specificity of multiple quantum wells, i.e. a strong enhancement of the photo-conductivity transients, up to thousands of seconds, which is observed for excitation energies corresponding to the yellow band (2.2 eV) in quantum wells, whose PL spectra did not show any evidence of YB emission.

SESSION E5: DEFECTS
Chair: Peter M. Asbeck
Wednesday Afternoon, April 18, 2001
Salon 1/2 (Marriott)

1:30 PM E5.1
FREQUENCY RESPONSE OF TRAP STATES IN AN $Al_xGa_{1-x}N$/GaN HETEROSTRUCTURE FIELD-EFFECT TRANSISTOR MEASURED AT THE NANOSCALE BY dC/dV SPECTROSCOPY. Daniel M. Schaadt, Edward T. Yu, Dept of Electrical and Computer Engineering, Univ of California at San Diego, La Jolla, CA; Joan M. Redwing, ATMI/Epitronics, Phoenix, AZ.

Scanning capacitance spectroscopy has been used to characterize, at the nanoscale, the frequency-dependent response of surface charges and of charge in the two-dimensional electron gas (2DEG) of an $Al_xGa_{1-x}N$/GaN heterostructure field-effect transistor structure. dC/dV spectra were obtained as functions of tip-sample bias voltage in a scanning capacitance microscope, with the applied voltage signal consisting of a triangle wave at frequencies of 1-50 Hz. Spectra were obtained in the dark (except for 600 nm laser light from the scanning capacitance apparatus) and in the presence of ultraviolet (UV) illumination. Measurements were performed in the vicinity of and far away from threading dislocations visible in scanning capacitance images. In the absence of UV illumination, the observed dC/dV spectra indicate that electrons are trapped at or near the $Al_xGa_{1-x}N$ surface when negative bias voltages are applied to the sample, consistent with suggestions in the literature that a high density of surface states exists on the free $Al_xGa_{1-x}N$ surface. Frequency-dependent measurements indicate that, upon application of positive sample bias voltages, emission times for these traps can be as long as several hundred ms. In the presence of UV illumination, features in the dC/dV spectra associated with charging of surface traps are, as would be expected, largely absent. The nature and behavior of trap states in the vicinity of threading dislocations is found to differ significantly from that in regions between dislocations. Detailed characterization and analysis of these effects near and away from threading dislocations will be presented.

1:45 PM E5.2
SPECTROSCOPIC INVESTIGATION OF TRAPS PRODUCING CURRENT COLLAPSE IN AlGaN/GaN HEMT STRUCTURES. P.B. Klein, S.C. Binari, A.E. Wickenden , D.D. Koleske and R.L. Henry, Naval Research Laboratory, Washington, DC.

Recently, it was shown [1,2] that signatures of deep traps responsible for current collapse (CC) in GaN MESFET structures can be obtained by photoionization spectroscopy. In these measurements, the spectral dependence of the light-induced increase in the collapsed drain current is shown to reflect the photoionization cross-section of the trap. It was concluded from these studies that two distinct traps are responsible for CC in the MESFET, and that these traps reside in the high-resistivity (HR) GaN layer. In the present work, these measurements have been extended to the more complicated AlGaN/GaN HEMT structures. In principle, traps in these structures can reside either at the surface, in the AlGaN layer, at the interface, or in the HR-GaN layer. The devices were fabricated on materials grown on sapphire by MOCVD. The HR-GaN layers for these materials were prepared as a function of growth pressure in order to vary the incorporation of deep trapping centers. In all cases, the photoionization spectra revealed that the same two traps that were observed in the GaN MESFETs were also responsible for current collapse in the HEMT structures. This determines that the location of the responsible traps is in the HR-GaN layer of the HEMT structure. Variation in the MOCVD growth pressure is observed to result in large changes in the observed current collapse. This sensitivity to growth pressure appears to be associated with one specific trap, whose origin is presently under investigation. [1] P.B. Klein, J.A. Freitas, Jr., S.C. Binari and A.E. Wickenden, Appl. Phys. Lett, 75, 4016 (1999). [2] P.B. Klein, J.A. Freitas, Jr., S.C. Binari and A.E. Wickenden, J. Appl. Phys. 88, 2843 (2000).

2:00 PM E5.3
GENERATION-RECOMBINATION NOISE IN GaN/AlGaN HETEROSTRUCTURE FIELD-EFFECT TRANSISTORS. Alexander Balandin Univ of California - Riverside, Dept of Electrical Engineering, Riverside, CA.

Wide band-gap semiconductors such as GaN, AlN and their ternary alloys have been extensively investigated in recent years because of their potential microwave and optoelectronic applications. Advances in GaN-related compound materials and heterojunction field-effect transistors (HFETs) have already led to a demonstration of the high frequency and high-power-density operation of these devices. At the same time the absence of native substrates for epitaxial growth of II-V nitrides, and significant mismatch in the lattice constants and coefficient of thermal expansion for nitrides and sapphire substrates usually results in high defect concentrations, and correspondingly high low-frequency noise levels in these devices. In this presentation I will review the latest results of our investigation of low-frequency noise in GaN HFETs [1-2]. Particular emphasis will be on a theoretical method of extracting information about traps in GaN/AlGaN heterostructures from the low-frequency noise spectra with distinctive generation-recombination (G-R) bulges. The trap activation energy, capture cross-section, and concentration will be determined. It will be shown that the value of flicker noise is highly sensitive to the presence of crystal imperfections and, under certain conditions, can be used as a diagnostic tool for materials quality and reliability of GaN devices. The presence of piezoelectric fields at the GaN/AlGaN heterointerface leads to a redistribution of carriers and affects both the carrier density and carrier mobility fluctuations. The size effects in scaled down transistors on the flicker noise level will also be discussed. 1. A. Balandin, IEE Electronics Letters, 36 (10), 912 (2000). 2. A. Balandin, K.L. Wang, S.J. Cai, R. Li, C.R. Viswanathan, E.N. Wang, M. Wojtowicz., J. Electron Materials, 29: 297 (2000).

2:15 PM E5.4
RECOMBINATION AT SURFACE STATES IN GaN. M.A. Reshchikov, K.M. Jones, and H. Morkoc, Virginia Commonwealth University, Richmond, VA; P. Visconti, Virginia Commonwealth University, Richmond, VA; and Istituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY; R.J. Molnar, MIT Lincoln Lab., Lexington, MA; C.W. Litton, Air Force Research Laboratory, Wright Patterson AFB, OH.

Recent studies demonstrated that surfaces play an active part in recombination of free carriers in GaN affecting the performance of devices. We have studied radiative and nonradiative recombination at surface states in GaN, including as-grown samples and those treated with acids or bases. The surface states manifested themselves in two ways: (i) a reversible decrease of the photoluminescence (PL) intensity after exposure to air and (ii) appearance of new PL bands after treatment with acid or base and subsequent exposure to air. It has been established that GaN surface physi-sorbs species from air (presumably oxygen) which induce surface states acting as nonradiative recombination centers. These species can be removed, at least partially, in vacuum as a result of photo-induced desorption. It has been found that nonradiative recombination of photogenerated carriers via surface states comprises more than 70% of the recombination in some GaN samples. Another type of the surface state, which participates in radiative recombination, has been found in GaN samples after etching in hot acid or base and subsequent exposure to air. In such samples, a broad PL band emerges in the blue region of a spectrum at low temperatures. The blue band has been attributed to transitions of photogenerated electrons from donors in the near-surface depletion region to the surface states introduced by the above-mentioned procedure. The observed large blue-shift of the blue band with excitation intensity, quenching of the PL with increasing temperature, bleaching of the blue band intensity in time and nonexponential decay of the PL intensity after pulse excitation support the suggested model. The changes in the GaN surface caused by etching were examined by atomic force microscopy (AFM). In

some samples the blue band appeared even when no evidence of the layer etching was found except quite shallow etch pits formed at dislocation sites. The emerging blue band can be related to the surface states formed on a-planes of etch pits.

2:30 PM E5.5
DISLOCATION ELECTRICAL ACTIVITY IN III-NITRIDE FILMS. J.W.P. Hsu, M.J. Manfra, D.V. Lang, S. Richter, S.N.G. Chu, and A.M. Sergent, Bell Labs, Lucent Technologies, Murray Hill, NJ; R.J. Molnar, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, MA.

Compared to other III-V materials, light emitting diodes made of III-nitride materials are surprisingly insensitive to the high density of dislocations present in the films. However, the effect of dislocations in III-nitride lasers and electronic devices is less established. Hence, it is important to understand how dislocations change local electronic transport. Due to their high densities, spatially resolved techniques are necessary to separate out the dislocation contribution. In scanning current-voltage microscopy (SIVM), a conducting tip makes a microscopic size Schottky contact with the sample. Rastering the tip on the sample surface provides a mean to map spatial variation of current distribution at a given bias. We found that under reverse bias, leakage in MBE GaN and AlGaN/GaN is highly non-uniform with most of the current concentrated in isolated small regions. The size of these leakage regions increases with increasing reverse bias. By comparing with topographic images and TEM results, we show that reverse leakage occur predominantly at dislocations with screw components. Under forward bias, current is depleted in a region of radius ~200 nm around the dislocation core. These spatial revolved results are the first direct evidence for trapped negative charges at the dislocation cores with surrounding space charge regions. However, the manifestation of these electric behaviors depends on growth methods and conditions. Both SIVM and macroscopic Schottky diode results show that MBE films grown under Ga-rich conditions have orders of magnitude higher reverse bias leakage than HVPE films. Hence, the dislocation electrical activity is sensitive to its local environment and may be tuned for different applications.

3:15 PM E5.6
PHOTOLUMINESCENCE AND EXCITATION SPECTRA OF DEEP DEFECTS IN GaN. M.A. Reshchikov and H. Morkoc, Virginia Commonwealth University, Richmond, VA; R.J. Molnar, MIT Lincoln Laboratory, Lexington, MA.

Photoluminescence (PL) and PL excitation (PLE) spectra give important information about deep-level defects in wide-bandgap semiconductors. We applied these methods to investigate defects responsible for a set of broad PL bands in undoped wurtzite GaN. The layers for study were grown on the c-plane of sapphire by hydride vapor phase epitaxy (HVPE) and molecular beam epitaxy (MBE) with ammonia (NH3-MBE) or RF plasma (RF-MBE) as a source of nitrogen. In HVPE grown samples, a yellow luminescence (YL) and a red luminescence broad bands were observed, respectively, at about 2.2 and 1.93 eV. In NH3-MBE grown samples, the YL band dominated the defect PL spectrum, whereas in RF-MBE grown samples, new green (maximum at 2.4 eV) and red (1.88 eV) PL bands dominated the defect spectrum under certain growth conditions. It has been established from the variation of measurement temperature and the excitation intensity that the above-mentioned four bands are related to different deep-level defects. A PLE spectrum was undertaken for the above-mentioned PL bands at low and room temperatures. The PLE spectrum involves transitions related to resonant excitation of particular defect and transitions related to indirect excitation of the defect, i.e. when free carriers participate in the recombination. The shape of the PL and PLE spectra was analyzed in terms of one-dimensional configuration coordinate model.

3:30 PM E5.7
Abstract Withdrawn.

3:45 PM E5.8
DEFECT INVESTIGATION OF GaN THIN FILMS ETCHED BY PHOTO-ELECTROCHEMICAL AND HOT WET ETCHING BY ATOMIC FORCE AND TRANSMISSION ELECTRON MICROSCOPY. P. Visconti, Virginia Commonwealth University, Richmond, VA and Istituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY; K.M. Jones, M.A. Reshchikov, R. Cingolani, and H. Morkoc, Virginia Commonwealth University, Richmond, VA; R.J. Molnar, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, MA; D.J. Smith, Dept. of Physics and Astronomy and Center for Solid State Science, Arizona State University, Tempe, AZ.

The availability of reliable and quick methods to investigate defects in GaN films is of great interest. Photo-electrochemical (PEC) etching, and wet etching using both hot H_3PO_4 acid and molten KOH have been used to study structural defects in GaN layers grown by hydride vapor phase epitaxy and molecular beam epitaxy. The purpose of this work is to determine whether, and under what conditions, these different methods of investigation are consistent in order to get to a more accurate estimation of the defect density. As-grown and etched surfaces were observed by tapping-mode atomic force microscopy (AFM), and plan-view and cross-sectional transmission electron microscopy (TEM). Freestanding whisker-like features and hexagonal-shaped etch pits are formed on the etched sample surfaces by PEC and wet etching, respectively. Using plan-view AFM, we find the density of whisker-like features ($8x10^8$ -$1x10^9$ cm^{-2}) to be similar to the etch pit densities for samples etched with both H_3PO_4 and molten KOH under very precise etching conditions. During the wet etching process, a careful balance must be struck to ensure that every defect is delineated, but not overetched to avoid underestimating the defect density. Additionally, the TEM observations carried out on as-grown and etched samples confirmed dislocation densities obtained by etching which increased our confidence in the consistency of the methods used.

4:00 PM E5.9
THE EFFECT OF RESIDUAL IMPLANT DAMAGE ON BORON-NITROGEN DOPANT INTERACTIONS IN IMPLANTED 4H-SiC BIPOLAR TECHNOLOGY. N.G. Wright, G.J. Phelps, A.B. Horsfall, C.M. Johnson, A.G. O'Neill, Dept. of Electrical Engineering, The University of Newcastle, UNITED KINGDOM; P.G. Coleman, Dept. of Physics, The University of Bath, UNITED KINGDOM.

Accurate predictions of doping profiles is crucial for advanced bipolar device fabrication in 4H-SiC. In practical implanted power devices, it is necessary to implant multiple species of ions to achieve the complex doping structures required. In this paper, the effect of implant damage on boron-nitrogen dopant interactions is investigated. It is shown that such interactions result in both deviations from predicted doping levels and substantially increased nitrogen diffusion under common anneal conditions leading to potential problems with device realization. Physical models for understanding and predicting these processes will be discussed.

4:15 PM E5.10
SURFACE EVALUATION OF 6H-SiC AFTER DOPING BY DIFFUSION. Ying Gao, S.I. Soloviev, T.S. Sudarshan, Univ of South Carolina, Dept of Electrical Engineering, Columbia, SC.

Surface morphology is very critical for device fabrication. Basically, diffusion process in SiC involves a high temperature treatment, which may cause severe surface deterioration of SiC due to epigrowth, sublimation or chemical reaction. Thus, the evaluation of the wafer surface is one of the essential aspects to determine the applicability of diffusion in practice. Boron and aluminum doping of 6H-SiC samples via diffusion has been realized in the temperature range of 1800-2100°C. Atomic Force Microscopy (AFM) has been used for characterizing surface roughness, a basic parameter of wafer surface, before and after diffusion. AFM images clearly show regular furrows on the surface due to SiC sublimation during diffusion and also reveal high surface roughness (more than 20 nm in comparison with less than 1nm in virgin samples). This definitely will have a significant influence on device performance. In order to reduce or eliminate this surface deterioration, a thin graphite mask is formed on the sample surface. The thickness of the mask is chosen to eliminate surface sublimation on one hand, and allow dopant atoms to penetrate into the substrate on the other hand. The influence of the mask on the impurity atom depth distribution is discussed based on SIMS measurements. Significant improvement has been obtained in that the surface roughness drops back to around 1.5nm. Atomic ratio of Si/C in the surface was measured by X-ray Photoeletron Spectroscopy (XPS) and Energy Dispersive Spectroscopy (EDS), which shows that a post-treatment oxidation can greatly improve recovery of the surface stoichiometry.

4:30 PM E5.11
INFRARED ABSORPTION AND ANNEALING BEHAVIOR OF SEMI-INSULATING 4H SiC HTCVD SUBSTRATES.
B. Magnusson[a], A. Ellison[b], N.T. Son[a], J. Zhang[a], and E. Janzén[a], [a]Dept of Physics and Measurement Technology, Linköping University, SWEDEN; [b]Okmetic AB, Linköping, SWEDEN.

Semi-insulating substrates are needed for SiC applications like high-frequency devices. The quality of the substrate will have large impact of the device that should be manufactured. The three most important factors are resistivity, trapping effects, and thermal conductivity. These factors are affected by the purity and deep levels concentration of the material and it has been shown that, the purity of the high temperature CVD (HTCVD) grown wafers give an excellent result on trapping effects as compared to vanadium doped semi-insulating wafers.
In this work we have concentrated on the intrinsic point defects and

complexes which are introduced in the material during growth. These defects are usually negligible in vanadium doped substrates, but in the case of HTCVD material one needs to take them into account since these intrinsic defects can exist at the same concentration as residual impurities. Due to the purity of the investigated samples, thicknesses up to 5 mm have to be used in absorption measurements. Most intrinsic defects have previously been considered to be quenched with annealing at CVD growth temperatures, and were therefore not assigned to contribute to the high resistivity of undoped semi-insulating material, which stands a 1600°C anneal. This assumption, based on studies of irradiated material, is shown to be not valid for as-grown material.
We will present infrared absorption measurements of semi-insulating HTCVD wafers at different annealing temperatures. The results show that not all intrinsic infrared absorption centers are quenched with 1600°C annealing. A discussion on the influence of intrinsic defects on the semi-insulating material properties will also be presented. The discussion is based on the comparison between infrared absorption measurements of deep levels and the resistivity of of semi-insulating HTCVD substrates grown under various conditions.

SESSION E6: CONTACTS TO GaN AND SiC
Chair: Primit Parikh
Thursday Morning, April 19, 2001
Salon 1/2 (Marriott)

8:30 AM *E6.1
GaN POWER HEMTS FOR MMWAVE APPLICATIONS. Y.-F. Wu, P. Chavarkar, M. Moore, P.A. Parikh, U.K. Mishra, Cree Lighting Company, Goleta, CA.

Due to the superior electron transport properties, GaN-based high-mobility-transistors (HEMTs) have shown tremendous potential in power generation at microwave frequencies. Current state-of-the-art include power densities > 9 W/mm at 8 GHz from small devices , as well as a total CW power > 20 W at 9 GHz using four 1-mm-wide devices , a pulsed output power of 40 W at 10 GHz from a GaN on SiC MMIC using a 12 mm device and a pulsed output power of 51 W at 6 GHz from an amplifier IC using a 8-mm-wide device . These are about 8-10 times improvement over GaAs counterparts. Recent results from different groups show that AlGaN-GaN HEMTs are capable of high power performance at mm-wave frequencies, which will be the focus of this presentation. The devices were grown by metal-organic-chemical-vapor deposition on semi-insulating SiC substrates. The epi-layers consisted of an insulating GaN buffer and a modulation-doped AlGaN layer to supply charge for the 2-dimensional gas as well as to form the Schottky-gate barrier. The Al composition was greater than 30%. The footprints of the gates were ∼0.2 mm with a T-top of ∼0.7 mm, which were defined by electron-beam lithography. These sub-micrometer gate-length devices showed current densities of 1.2-1.6 A/mm and breakdown voltages of ∼50 V. The current-gain and power gain cut-off frequencies (ft and fmax) were measured as 60 GHz and 120 GHz, respectively, for the devices with gate dimensions of 0.2x100 mm2. 5 W/mm of output power was obtained at 26 GHz with 25% PAE at a drain bias of 25 V. The linear gain was ∼12 dB and the saturated gain was ∼7 dB. With optimum matching for high efficiency at 26 GHz, 33% PAE with 3.2 W/mm was realized. Applications for this new generation of microwave power amplifiers range from wireless communication broadband access applications such as LMDS, Digital Radios, Gateway Terminals for Satellite Communications, Communication Satellite Transponders on the commercial front to Radar Systems and mm-wave DOD systems on the military arena at frequencies ranging from 12-44 GHz.
Acknowledgements: This work was sponsored by Dr. J. Zolper, Office of Naval Research. T. Jenkins, L. Kehias, Wright Patterson Air Force Base, Dayton-Ohio assisted in the mm-wave measurements and E. Caine, UCSB assisted in the E-beam Lithography.

9:00 AM E6.2
OHMIC CONTACTS TO HIGH Al-FRACTION AlGaN.
K.O. Schweitz and S.E. Mohney, Dept of Materials Science & Engineering, The Pennsylvania State University, University Park, PA; M. Pophristic, D. Gotthold, I. Ferguson, Emcore Corp., Somerset, NJ.

Ohmic contacts to AlGaN or structures containing AlGaN are necessary for a variety of devices such as heterojunction field effect transistors and UV detectors. We have achieved ohmic behavior on n-$Al_xGa_{1-x}N$ with $0.31 \leq x \leq 0.60$, but x=0.4 is the highest Al fraction for which contacts so far exhibit good uniformity. A specific contact resistance of $(7 \pm 5) \times 10^{-6}$ Ωcm^2 to $Al_{0.4}Ga_{0.6}N$ is achieved using Ti/Al/Pt/Au multilayered contacts. This is the highest Al-fraction AlGaN for which ohmic contact formation has been reported. The influence of pretreatment, annealing gas, and contact composition on the ohmic contact formation and the corresponding contact resistivities are investigated by 30 s isochronal annealing experiments between 500 and 1000°C. The contact resistivities of Ti(x nm)/Al(100-x nm)/Pt(50nm)/Au(50nm) contacts with x= 34 all reveal the same behavior as a function of annealing temperature regardless of pretreatment and annealing gas: the specific contact resistance exhibits a minimum of $(2.0 \pm 0.5) \times 10^{-4}$ Ωcm^2 at 800°C, which does not improve by pretreating the degreased AlGaN surface with 10% HCl or 10% buffered oxide etch (BOE) and/or changing the annealing gas from N_2 to Ar. However, decreasing the Ti/Al ratio in the contacts by changing x to 26 and 17 monotonically lowers the minimum contact resistivity to $(7 \pm 5) \times 10^{-6}$ Ωcm^2 for the x= 17 sample. The temperatures at which minimum specific contact resistances occur are again 800°C for the x= 26 sample, whereas it changes to 950°C for the x= 17 sample. The top Au layer is found to play an active role in forming an ohmic contact with low resistance, since omitting the Au layer in an x = 34 sample yields an increase in specific contact resistance of almost two orders of magnitude at 800°C. Furthermore, leaving out the Au layer requires the sample to be annealed at 700°C or higher in order to form ohmic contacts, as opposed to 500°C when the Au layer is present. These findings are discussed with respect to the composition profiles and phases measured by X-ray photoelectron spectroscopy depth profiling, Rutherford backscattering spectroscopy and X-ray diffraction.

9:15 AM E6.3
EFFECTS OF Au OVERLAYER ON THE THERMAL STABILITY OF Pt-BASED OHMIC CONTACTS ON P-TYPE GaN.
Jong Kyu Kim, Yu-Hwa Cho, Jong-Lam Lee, Dept of Material Science & Engineering, Pohang Univ. of Science and Technology, Pohang, SOUTH KOREA; Jae Won Lee, Yong Jo Park, Taeil Kim, Samsung Advanced Institute of Technology, Photonics Lab, Suwon, SOUTH KOREA.

Thermally stable and low resistance ohmic contacts on p-type GaN are essential in developing CW blue laser diodes. Pt-based ohmic contacts on p-type GaN displayed low contact resistance ($\sim 10^{-4} \Omega \cdot cm^2$), however, no works were conducted on their thermal stability. In the present work, thermal stabilities of both Pt and Pt/Au ohmic contacts on p-type GaN were studied through high temperature acceleration test. The results obtained were used to interpret the degradation mechanism and the effect of Au over layer on thermal stability of Pt contact on p-type GaN. Two types of metal schemes, Pt single layer (200 Å) and Pt (200 Å)/Au (500 Å), were deposited on the p-type GaN(p=$1.9 \times 10^{17} cm^{-3}$) grown by MOCVD. The metal contacts with TLM structures were annealed for thermal acceleration test at 550°C, and the change of contact resistivity was monitored. Interfacial reaction and elemental diffusion between metal with p-type GaN during the thermal stress were analyzed using x-ray scattering, SIMS and AFM. The contact resistivity of Pt on p-type GaN was $1.3 \times 10^{-3} \Omega \cdot cm^2$ and rapidly increased to show rectifying behavior after thermal stress for 2 hours, however, that of Pt/Au contact was $1.5 \times 10^{-3} \Omega \cdot cm^2$ and maintained ohmic behavior even after 50 hours. In the x-ray scattering analysis, epitaxial relationship between Au/Pt/GaN and the change of inter-planar spacing of Au (111) were found. In the SIMS analysis, Ga atoms were detected in Au overlayer in Pt/Au cotnact. This suggests that Ga atoms were outdiffused to Au layer through grain boundaries of Pt, and a solid solution of Ga in Au layer was formed during the thermal stress. Using these experimental results and thermodynamic consideration, band diagram for both contacts will be provided and thermal degradation mechanism of ohmic contact on p-type GaN will be proposed.

9:30 AM E6.4
EFFECTS OF PLASMA SURFACE TREATMENT ON OHMIC CONTACT TO N-GaN. E.F. Chor and X.J. Kang, Center for Optoelectronics, Department of Electrical and Computer Engineering, National University of Singapore, SINGAPORE.

Plasma-induced damage has known to degrade the electrical and optical properties of III-V nitride electronic and photonic devices. We have investigated the effects of plasma surface treatment on ohmic contacts to n-type GaN. Prior to metal evaporation, n-GaN surface was etched either chemically using aqua-regia (control sample) or by means of inductively coupled Cl_2/BCl_3, N(2) or Ar plasmas. The metal system adopted in our investigation was Ti/Al/Pd/Au. The as-deposited Ti/Al/Pd/Au contact on aqua-regia treated n-GaN exhibits an ohmic behavior with a specific contact resistance (ρ_c)of $2 \times 10^{-4} \Omega cm^2$. After annealing at 500°C for 5min, ρ_c is reduced by approximately 2 orders of magnitude to $5 \times 10^{-6} \Omega cm^2$. For Cl_2/BCl_3 and N_2 plasma treated n-GaN surface, the as-deposited Ti/Al/Pd/Au contacts also yield ohmic behavior and ρ_c's are about $2 \times 10^{-4} \Omega cm^2$ and $5 \times 10^{-4} \Omega cm^2$ respectively. After annealing at 500°C for 5min, ρ_c's are reduced by about 3 orders of magnitude to around $5 \times 10^{-7} \Omega cm^2$ and $8 \times 10^{-7} \Omega cm^2$ respectively. On the other hand, the as-deposited Ti/Al/Pd/Au contact on Ar plasma treated n-GaN exhibits a non-ohmic behavior. After annealing at 500°C for 5min, ρ_c is about $5 \times 10^{-7} \Omega cm^2$ and the lowest ρ_c of $7 \times 10^{-8} \Omega cm^2$ is obtained after annealing at 700°C for 5min. The contacts on other surface

treated n-GaN are found to degrade at 700°C annealing. By comparing the values of ρ_c for various surface treatments, particularly those after annealing, it is observed that plasma etching can be used beneficially in the formation of ohmic contacts - plasma surface treatment using Cl_2/BCl_3, N_2 or Ar has resulted in an order of magnitude reduction in ρ_c compared to chemical surface treatment by aqua-regia. As ρ_c's are reduced significantly after rapid thermal annealing for plasmas etched samples, it may also be inferred that rapid thermal annealing is effective in removing some of the inductively coupled plasmas induced damage. Currently, we are investigating the influence of the rf-power and the plasma d.c. self-bias voltage. Keywords: GaN, inductively coupled plasma (ICP), ohmic contact.

9:45 AM E6.5
STABLE LOW RESISTANCE OHMIC CONTACTS TO p-GaN. MiRan Park and Wayne A. Anderson, State University of New York at Buffalo, Electrical Engineering Department, Buffalo, NY.

Stable and low-resistance Ohmic contacts are especially important for laser diodes where high current levels are required. Good contacts are especially difficult on p-type GaN which was the motivation for this study. The GaN was epitaxially grown on (0001) sapphire substrates by MOCVD. Resistivity of this layer was 3.5 Ohm-cm and thickness was 2 microns. After conventional cleaning followed by treatment in boiling HNO_3:HCl (1:3), metallization was by thermally evaporating 40 nm Au / 65 nm Ni or 70 nm Au / 55 nm Pd. Heat treatment in O_2 + N_2 at various temperatures followed, with best results at 600°C or 700 °C, respectively. Best values of resistance were 1.8 x 10^{-4} Ohm-cm for Pd and 2.65 x 10^{-4} Ohm-cm for Ni contacts. After repetitive cycling from room temperature to 600°C, the Ni contacts were very stable and more stable than the Pd contacts. X-ray photoelectron spectroscopy depth profiling showed the Ni contacts to be NiO followed by Au at the interface for the Ni contacts whereas the Pd contacts exhibited a Pd:Au solid solution. Some contacts were quenched in liquid nitrogen following sintering. These contacts were much more uniform under atomic force microscopy examination and gave a 3 times lower contact resistance with the Ni/Au design. Current-voltage-temperature analysis revealed that conduction was predominantly by thermionic field emission.

10:30 AM E6.6
NON-ALLOYED AlGaN/GaN HETEROSTRUCTURE FIELD EFFECT TRANSISTOR, THROUGH PRE-TREATMENT OF SURFACE BEFORE METALIZATION. Chang Min Jeon, Ho Won Jang, Jong-Lam Lee, J.H. Lee[a], S.B. Bea[a], Dept of Material Science & Engineering, Pohang University of Science and Technology Pohang, KOREA. [a]Dept of Electronic and Electrical Engineering, Kyunpook National University Teagu, KOREA.

Reducing gate length and specific contact resistivity of ohmic contacts is important in the realization of AlGaN/GaN heterostructure field effect transistor (HFET). As gate length is reduced, the space between source and drain becomes narrow, which makes it difficult to align and produce a fine gate pattern. If the ohmic contact is formed at room temperature, fine pattern is obtained due to the increase of process flexibility. Surface treatment before metal deposition could produced point defects at the surface of AlGaN. These defects, locating in the bandgap, could acting donors or acceptors. Thus, Fermi level could be pinned at those defects, leading to ohmic behavior, namely non-alloyed ohmic contact on AlGaN. However no works were conducted on non-alloyed ohmic contacts in the fabrication of HFET. Three types of plasma were applied to AlGaN, and then several kinds of metals were deposited. The contact resistivity and Schottky barrier height (SBH) were measured using TLM and I-V method. The atomic composition on the treated surface was analyzed using synchrotron radiation photoemission spectroscopy. The oxygen plasma treated AlGaN showed the lowest SBH, and good ohmic contact behavior, but Ar plasma treated AlGaN indicated high SBH. In addition, the SBH was not related to the metal work function of undoped AlGaN. It was formed that atomic percent of Ga was greater than that of N and energy difference between VBM and Fermi was changed by the plasma treatment. In case of Cl_2 plasma treatment, a low contact resistivity of $10^{-4}\Omega cm^2$ was demonstrated using Ti contact on the undoped AlGaN. From these results, non-alloyed ohmic contact heterostructure field effect transistor was fabricated using the pre-treatment of plasma etching.

10:45 AM E6.7
IMPROVED LOW RESISTANCE OHMIC CONTACT OF Pd/Ni ON P-TYPE GaN. Ho Won Jang, Chang Min Jeon, Jong Kyu Kim and Jong-Lam Lee, Pohang University of Science and Engineering, Dept of Material Science & Engineering, Pohang, KOREA; Soon Won Hwang, Sung Jin Son, Knowledge on Inc., Iksan, KOREA.

A low resistance ohmic contact on p-type GaN is essential for good performance of electronic and optoelectronic devices such as blue light emitting diodes and laser diodes. The Pd/Au bilayer contact is widely used for fabrication of these GaN devices. The main reason of low contact resistance is due to high work function and the stable electrical and thermal properties. The Au overlayer which acts as a protection metal layer prevents or slow down the degradation of contact resistance under a suitable annealing condition. A new ohmic contact scheme of Pd/Ni on p-type GaN is presented in this work. The contact resistance is compared with that of Pd/Au. The samples were dipped into boiling aqua resia solution for 10 min to remove native oxides and surface contamination, followed by metal depositions using electron beam evaporator. The contact resistance was measured using a transmission line method. The improvement of contact resistance by the Ni overlayer on Pd was investigated using x-ray diffraction (XRD) and high resolution electron microscopy (HREM). The specific contact resistance of Pd/Ni was reduced to 3 x 10^{-4} Ωcm^2 by an order of magnitude compared to 2 x 10^{-4} Ωcm^2 for Pd/Au under the same optimum annealing condition, 500°C. XRD has shown that Pd (111) peak shifts toward the higher angle and its height is decreased with the increase of annealing temperature. The solid solution of Pd and Ni was observed from HREM after the annealing. From these results, it is suggested that Pd-Ni solid solution layer is formed at the interface of Pd/Ni and results in preventing Ga and N out-diffusions under the annealing condition. Thus Ga vacancies are created by the reaction of Pd and Ga at the interfacial region which remains a N-rich condition subsequently.

11:00 AM E6.8
PROPERTIES OF GaN SCHOTTKY DIODES WITH DIFFERENT POLARITY. Uwe Karrer, Oliver Ambacher, and Martin Stutzmann, Walter Schottky Institut, Technische Universität, München, GERMANY.

A key property of wurtzite group III nitrides is their large spontaneous and piezoelectric polarization, which strongly influences the performance of electronic and optoelectronic devices. In relaxed GaN, the total polarization is dominated by the spontaneous polarization and their orientation is determined by the crystal polarity. Si-doped epitaxial GaN layers with Ga- and N-face polarity were grown by plasma-induced molecular-beam epitaxy (PIMBE) in order to characterize the influence of polarity on the electrical performance of Schottky diodes. Various metals were used as Schottky contacts exhibiting different barrier heights on the different faces. Using IV-measurements, the zero bias barrier height is deduced from the dependence of the effective barrier height versus ideality factor. The best experimentally obtained ideality factors were 1.1. The barrier heights for Ga-face GaN are up to 0.2 eV higher compared to N-face GaN, with the greatest values for Pt, Au, and Pd of 1.1 eV. C-V measurements confirm the result of greater barrier heights for Ga-face material, but lead to higher absolute values of the Schottky barriers. Activation energy and photothreshold measurements are presented to further support these findings. Furthermore, comperative studies for Pt Schottky contacts on the different sides of freestanding GaN grown by hydride vapor phase epitaxy (HVPE) give similar results. The slope parameters in the plot of barrier height versus electronegativity of metals deposited on Ga- and N-face GaN, can be inferred for the first time for GaN with both polarities. A model to explain the obtained results is proposed based on the self-consistent solution of the Schrödinger-Poisson equation for epitaxial layers with different polarity. Polarization-induced surface and interface charges are included leading to different band bending of the conduction and valence band and, thus, resulting in accumulation and inversion layers of free carriers at opposite surfaces.

11:15 AM E6.9
CORRELATION BETWEEN MORPHOLOGY AND ELECTRICAL PROPERTIES OF NICKEL SILICIDE CONTACTS ON 6H-SiC. F. Roccaforte, St-Microelectronics, Catania, ITALY; F. La Via, V. Raineri, CNR-IMETEM, Catania, ITALY; P. Musumeci, L. Calcagno, Dipartimento di Fisica e Astronomia, Catania, ITALY.

Nickel is widely used for the realization of ohmic contacts in silicon carbide because of its ease to form silicides upon annealing even at moderate temperatures and the possibility of obtain low values of contact resistance. The formation of nickel silicide (Ni_2Si) on crystalline n-type 6H-SiC by means of thermal treatments of Ni/SiC samples was studied. The formation of Ni_2Si was monitored by means both of Rutherford backscattering spectrometry (RBS) and X-Ray diffraction (XRD), while the reaction kinetics was followed by in-situ sheet resistance measurement. The silicide could be observed already after 20 minutes annealing at 600°C of the Ni/SiC samples, which completely reacted at 800°C. Elemental microanalysis showed that carbon was almost uniformly distributed inside the reacted layer, being weakly accumulated at the silicide/SiC interface. The silicide/SiC samples were characterized electrically by measuring both the sheet resistance (Rs) and the contact resistance (rc). The sheet resistance of the Ni_2Si layer was higher than the value measured for the same phase on silicon. The latter can be ascribed to the presence

of carbon distributed in the layer. The contact resistance (rc) of the samples annealed at 950°C was measured by using the Transmission Line Method (TLM). The value of rc decreased with increasing doping concentration of the substrate, ranging between 2×10^{-4} Ω/cm^2 and 1×10^{-6} Ω/cm^2. In order to verify the stability of the contacts, the Ni_2Si/SiC samples were annealed at 950°C for longer times. The value of rc was about 10^{-5} Ω/cm^2 even after 5 hours annealing, thus indicating a good stability of the contact. The combination between Atomic Force Microscopy (AFM) and RBS was used to estimate the roughness of surface and interface of the films. This kind of analysis allowed to correlate the film morphology with the electrical properties of the silicide.

11:30 AM E6.10
CARBON GRAPHITIZATION AND ELECTRICAL PROPERTIES ON 4H-SiC. Candis A. Adams, Weijie Lu, W. Eugene Collins, Department of Physics, Fisk University, Nashville, TN; Ravi K. Chanana, Leonard C. Feldman, Department of Physics, Vanderbilt University, Nashville, TN; William C. Mitchel, Materials Directorate, Air Force Research Lab, Wright-Patterson AFB, OH.

Ohmic contact formation on SiC is one of the key technical issues in device fabrications. A high temperature annealing process is usually required to form Ohmic contact. It is well known that metal reacts with Si in SiC forming metal silicides, and carbon exists in the interfacial region during the annealing process. However, it is still not understood how Ohmic contact is formed on SiC and what the role of carbon formation is in the process. In this study, a carbon thin film was deposited on n-type, Si-face 4H-SiC with different doping concentrations of 1.3×10^{19}, 7.0×10^{18}, and 2.0×10^{18} cm^{-3}. The electrical properties of these samples were measured by the four-point method as deposited, and after being annealed at 600 and 950°C in Ar for 30 minutes, respectively. The sheet resistance of the samples shows a decrease after annealing at 600°C, and a significant decrease after annealing at 950°C, particularly, for the sample with the highest doping concentration. The morphology and surface compositions were characterized by X-ray photoelectron spectroscopy (XPS) and atomic force microscopy (AFM). The carbon graphitization occurred at 600°C. At 950°C, additional carbon formed due to preferential volatility of silicon in SiC, and the increase in the degree of graphitization contributed the decrease of the sheet resistance. Many factors affect the Ohmic contact formation on SiC, and this preliminary study is helpful in understanding the mechanism of Ohmic formation on SiC.

11:45 AM E6.11
OHMIC CONTACT FORMATION MECHANISM OF Ni-BASED CONTACT ON N-TYPE 4H-SiC. Sang Youn Han, Ki Hong Kim, Jong Kyu Kim, Ho Won Jang, Kwang Ho Lee, Jong-Lam Lee, Dept of Materials Science and Engineering, Pohang University of Science and Technology, (POSTECH) Pohang, KOREA; Nam-Kyun Kim, E.D. Kim, Power Semiconductor Group, Korea Electrotechnology Research Institute (KERI), Changwon, KOREA.

Ni-based contacts have been suggested as superior candidates of ohmic contact on SiC due to their low specific contact resistivity. It was thought that the reduction in contact resistivity is deeply related to the formation of Ni_2Si on SiC. In addition, it was often found that Al incorporation in Ni contact on 4H-SiC shows superior property. However, no works have been presented yet on the ohmic contact formation mechanism on Ni/SiC and Al effect on Ni-based contact, clearly. Two types of metal schemes, Ni single layer (1000 Å) and Ni(1000 Å)/Al(500 Å), were deposited on the n-type 4H-SiC (N_d=4.2 $\times 10^{15}/cm^3$). The metal contacts were annealed from room temperature to 1000°C by 100°C step, and measure the current-voltage characteristics and specific contact resistance using c-TLM method. Synchrotron XRD was employed to identify the created phases and the change of work function in contact metals with annealing temperature was analyzed by synchrotron radiation photoemission spectroscopy (SRPES). In the Ni contact, the Schottky barrier height was stable until 600°C annealing. On the contrary, Ni/Al contact shows thermal degradation at 400°C. After annealing at 950°C, the contact resistivity of Ni ($2.83\times 10^{-3}\Omega\cdot cm^2$) is better than Ni/Al contact ($5.38 \times 10^{-1}\Omega\cdot cm^2$). In the synchrotron x-ray scattering analysis of Ni contact, silicides with Si-rich phases were formed with increase of annealing temperature. In the SRPES secondary cut-off experiment, it was observed that work function decrease with the increase in Si-phase in silicide. From these results, ohmic contact formation mechanism of Ni contact on n-type 4H-SiC is proposed.

SESSION E7: PROCESSING GaN AND SiC
Chair: Chanh Nguyen
Thursday Afternoon, April 19, 2001
Salon 1/2 (Marriott)

1:30 PM E7.1
OPTICAL CHARACTERIZATION OF Mg- AND Si-IMPLANTED GaN. James A. Fellows, Yung Kee Yeo, Robert L. Hengehold, Air Force Institute of Technology, Wright-Patterson AFB, OH; Leonid Krasnobaev, Implant Sciences Corp, Wakefield, MA.

One of the problems with improving group-III nitride device technology is successful doping with acceptors. Ion implantation is one of the doping techniques, but the study of implantation doping of nitrides is still in its infancy, especially for p-type doping. In the present work, the electrical and optical properties of Mg- and Si-implanted GaN have been investigated as a function of anneal temperature using cathodoluminescence, photoluminescence, and Hall-effect measurements. The electrical activation efficiencies of Mg and Si implants were evaluated along with an assessment of the causes preventing efficient Mg activation in GaN. Implantation of Mg, Si, Mg Si, and Mg O was made into MBE-grown GaN at 200 keV for Mg and 220 keV for Si at room temperature, 500, and 800°C with doses of 10^{14} and 10^{15} cm^{-2}. The samples were capped with either 500 or 1000 Å AlN and annealed at 1050 to1200°C for 15 s to 20 min using either rapid thermal or furnace annealing. The luminescence spectra of the Mg-implanted and annealed GaN show two main peaks: a zero-phonon UV peak at 3.27 eV and a broad green luminescence (GL) band at 2.37-2.38 eV. The relative intensities of the UV peak and the GL band vary as a function of implantation temperature, ion dose, species, and anneal temperature. The UV peak can be attributed to a donor-acceptor pair (DAP) transition, and the broad GL band may be related to a deep donor-deep acceptor complex resulting from residual implant damage, growth defects, and/or the Mg implant. The UV DAP versus GL intensity roughly indicates the relative percentage of shallow Mg acceptor incorporation over Mg-related deep complex centers. These factors along with suggestions on how to improve the electrical activation efficiency of Mg implanted GaN will be reported here.

1:45 PM E7.2
EFFECT OF Be-O AND Mg-O CO-IMPLANTATION IN GaN. D.G. Kent, S.J. Pearton, B.P. Gila, and C.R. Abernathy, Department of Materials Science and Engineering, University of Florida, Gainesville, FL.

Several theory groups have predicted higher net acceptor concentrations in co-doped GaN and there has been some experimental support for this assertion in epitaxial cubic-GaN and in initial implantation experiments. We have co-implanted Mg^+ and O^+ and Be^+ and O^+ into insulating GaN and annealed at greater than 1150°C in both capless and AlN-encapsulated modes, in order to activate the implanted species. Hall measurements were performed to measure the activation efficiency of the acceptors in both single and co-implanted samples. We do not observe p-type doping under any condition with Be^+ implantation, which confirms that it likely has a large ionization energy in GaN. The Mg^+ implanted samples show subtle effects of the O^+ co-implantation and a mechanism by which one must be aware of the additional damage created by the O and its donor nature.

2:00 PM E7.3
Abstract Withdrawn.

2:15 PM E7.4
GADOLINIUM OXIDE GATE DIELECTRIC FOR COMPOUND SEMICONDUCTOR MOSFETS. B.P. Gila, K.N. Lee, V. Krishnamoorthy, C.R. Abernathy and S.J. Pearton, Dept of Material Science & Engineering, Univ of Florida, Gainesville, FL; J.W. Johnson, F. Ren, Dept of Chemical Engineering, Univ of Florida, Gainesville, FL.

Fabrication of high performance metal oxide semiconductor field effect transistors (MOSFETs) from compound semiconductors will require both good interfacial electrical characteristics and good thermal stability. This will require a clean, smooth interface and control of the substrate surface termination and oxide growth initiation. While dielectrics such as SiO_2 and $GdGaO_x$ have demonstrated low to moderate interface state densities, questions remain about their thermal stability and reliability, particularly for use in high power or high temperature widebandgap devices. In this paper we will discuss the utility of Gd_2O_3 as a dielectric material grown via gas source molecular beam epitaxy on GaN. Structures containing both amorphous and single crystal layers have been studied and have been found to produce layers with excellent surface morphologies as evidenced by surface roughnesses of less than 1.0nm as seen in AFM. Single crystal films were achieved at growth temperatures of 600°C to 650°C while amorphous films were achieved at growth temperatures below 200°C. Crystal structures were determined by RHEED, XRD, and TEM. For both microstructures, stoichiometric films were obtained. This paper will describe the relationship between growth initiation and growth conditions and their effect on material

characteristics for Gd_2O_3, and will present electrical characterization and thermal stability of capacitors and transistors fabricated from amorphous and crystalline Gd_2O_3 on GaN and from hybrid layered structures containing both.

2:30 PM E7.5
IMPROVEMENT OF CARBON-FACE SiC METAL OXIDE SEMICONDUCTOR STRUCTURES USING LOW TEMPERATURE OXIDATION. Wang Chun and M.E. Zvanut, University of Alabama at Birmingham, Birmingham, AL.

Most attempts at fabricating functional metal oxide semiconductor (MOS) structures using SiC involve oxidation of the Si-face between 1100 and 1200°C . Hoping to exploit the increased oxidation rate of the C-face, some have conducted oxidation studies on both polar faces. However, C-face structures consistently exhibit poor characteristics, most likely because the C-face is less stable than the Si-face at high temperature. To minimize deterioration of the SiC surface, we have performed low temperature oxidation of the carbon face. MOS capacitors were built on Si-face and C-face substrates with 10^{16}cm^{-2} N-doped epitaxial layers, and four types of oxidation conditions were compared. The voltage (V_o) measured at 1 μA on a 4.5×10^{-3} cm^2 contact and flat-band voltage (V_{fb}) extracted from the high frequency capacitance-voltage characteristic were used to estimate the quality of the oxide. Reported results for each type of sample are averages from approximately nine capacitors. As expected, 57 nm oxides grown on the Si face in steam at 1150°C show consistent V_o (35 V) and V_{fb} (7.7); however, the C-face structures exhibit erratic current-voltage curves with V_o as low as 10 V. Lowering the oxidation temperature to 950°C improved the oxide quality. A 40 min steam oxidation followed by a 50 min dry oxidation produces a higher quality oxide than either a 300 min dry oxidation or 60 min steam oxidation. Using the steam-dry combination, the best results we have obtained for a C-face 59 nm oxide are a V_o of 30 V and V_{fb} of 6.5 V. We will discuss further improvements to the C-face MOS structures obtained by post oxidation anneals, and we will examine the effects of oxidation temperatures between 600-1000°C.

SESSION E8: OTHER WIDE BANDGAP MATERIALS/DEVICES
Chair: Edward T. Yu
Thursday Afternoon, April 19, 2001
Salon 1/2 (Marriott)

3:15 PM E8.1
HIGH FREQUENCY PERFORMANCE OF DIAMOND FIELD-EFFECT TRANSISTOR. Hirotada Taniuchi, Hitoshi Umezawa, Takuya Arima, Minoru Tachiki and Hiroshi Kawarada, Waseda Univ, Dept of Electronics, Information and Communication Engineering, Tokyo, JAPAN.

The microwave-performance of diamond metal-semiconductor field-effect transistor (MESFET) has been investigated for the first time. Diamond is expected for high power and high frequency electric device due to high thermal conductivity, large band gap and low dielectric constant. When diamond films are deposited by plasma assisted chemical vapor deposition, the diamond surface is terminated by hydrogen, which leads to the sub-surface p-type conductivity without doping impurities. This sub-surface conduction, the depth of which is less than 10 nm, is suitable for device fabrication because of shallow acceptor level and high carrier concentration. Due to hydrogen-termination, the density of surface pinning state is very low. Recent research shows that high performance DC characteristics MESFET have been fabricated on hydrogen-terminated diamond surface with transconductance of 110 mS/mm at 1 μm gate length [1]. In this report, using self-aligned gate fabrication process the MESFETs have been fabricated for RF-measurement on homoepitaxial (001) layer grown on high pressure and high temperature Ib synthesized diamond. The cut-off frequency and maximum frequency of oscillation of 2.2 and 7.0 GHz were obtained, respectively at 2 μm Cu-gate MESFET with maximum transconductance of 70 mS/mm. The maximum frequency of oscillation of 5.5 GHz and 1.2 GHz were obtained at 2.5 and 3.0 μm gate MESFET, respectively. Saturation of device characteristics due to the saturation of carrier velocity and short channel effect on 1 μm gate MESFET, it is expected that the transconductance of 120 mS/mm and cut off frequency of 8 GHz at the gate length of less than 1 μm with source-gate spacing of 0.1 μm. The improvement of device characteristics is expected by minimization of gate length and reduction of source resistance. Source resistance depends on high the sheet resistance of source-gate spacing due to shallow depth of surface conductive layer.
[1] H. Umezawa, K. Tsugawa, S. Yamanaka, D. Takeuchi, H. Okushi and H. Kawarada, Jpn. J. Appl. Phys., Vol. 38, pp.1222-1224, 1999.

3:30 PM E8.2
FABRICATION OF SUB-0.1 MICRON CHANNEL DIAMOND MISFET. Takuya Arima, Hirotada Taniuchi, Yoshikazu Ohba, Hitoshi Umezawa, Minoru Tachiki and Hiroshi Kawarada, Waseda Univ, School of Science and Engineering, Tokyo, JAPAN.

The p-type semiconductive layer of hydrogen terminated diamond surfaces exhibits desirable properties for the refined channel FET operation, such as high carrier concentration (10^{13} cm^{-2}) and shallow carrier profile (10nm in depth). In addition, CaF_2/Diamond interface exhibits a low density of surface states (less than 10^{11} cm^{-2}) [1]. Thus, the diamond surface has a great advantage for MISFET operation. Recently, utilizing this layer as channel, a Cu/CaF_2/Diamond MISFET with 1.1 μm gate length has been fabricated by the self-aligned process. The maximum transconductance of the MISFET exhibits 90 mS/mm [2]. This value is the highest in diamond MISFETs and is higher than those of SiC MOSFETs at present. The channel mobility is 280 cm^2/V·s. In the fabricated MISFETs at that time, 0.7 μm channel length was the shortest. In order to improve the performance of FETs, device miniaturization is indispensable. Thus, the purposes of this study are to fabricate deep sub-micron channel diamond FETs, to estimate the device characteristics, and finally to investigate the limit to the refinement. In the present study, the process for minimizing the channel length has been developed and Cu/CaF_2/Diamond MISFETs with 70-400 nm channel length have been succeeded in fabricating by this process. The produced MISFETs operate stably. The channel length of 70 nm is the shortest in diamond at present. The gate leakage current and hysteresis are hardly observed. The FETs of 70 nm channel length exhibit the short channel effect. For the suppression of the short channel effect, it is effective to epitaxially grow a thin undoped layer on a nitrogen-doped layer for the recombination of the holes with the electrons belonging to nitrogen donors.
[1]Y. Yun, T. Maki and T. Kobayashi: J. Appl. Phys. 82 (1997) 3422
[2]H. Umezawa and H. Kawarada et al: Jpn. J. Appl. Phys. 39 (2000) L908

3:45 PM E8.3
PROGRESS IN DIAMOND ELECTRONICS: CARRIER TRANSPORT AND DEVICE FABRICATION IN HYDROGENATED DIAMOND FILMS. Oliver Williams, Electronic Engineering, University College London, UNITED KINGDOM; Christoph Nebel, Walter Schottky Institute, Technical University of Munich, GERMANY; James E. Butler, Naval Research Labs, Washington, DC; John S. Foord, Physical and Theoretical Chemistry, University of Oxford, UNITED KINGDOM; Richard B. Jackman, Electronic Engineering, University College London, UNITED KINGDOM.

The realisation of efficient electronic devices from CVD diamond has been hindered by the lack of suitable dopants. Whilst boron (p), phosphorus (n) and sulphur (n) have all been demonstrated, they display relatively high activation energies rendering them unsuitable for use within structures that must be operated at or near room temperature. This situation has begun to change with the realisation by us and others that surface/near surface hydrogen is capable of generating p-type character with little thermal activation. Highly effective FETs have been fabricated from this form of diamond displaying, for example, full turn off and saturation charactersistics with the potential for high power handling. Despite this exciting development the origin of this form of conductivity has remained unclear. We have recently performed transport measurements at temperatures as low as 0.3K which confirm the presence of a band for conduction which displays minimal thermal activation and, even at this temperature, high carrier mobility values can be observed. This band appears to be associated with the presence of H-vacancy complexes. In this paper our current understanding of this new form of 'doping' will be discussed, alongside a presentation of the progress that we have made in fabricating highly effective transistors using this approach.

4:00 PM E8.4
BULK NITRIDE SUBSTRATES BASED ON ZINC OXIDE. Jeffrey E. Nause, Cermet, Atlanta, GA; Dave Look, Wright State University, Semiconductor Research Center, Dayton, OH; April Brown, Alan Doolittle, Georgia Institute of Technology, Atlanta, GA.

Single crystal zinc oxide (ZnO) is a potentially valuable material for many light emitter, detector, and power device applications. The tendency for the material to decompose at high temperature has precluded the crystallization from the melt. In this work, a high-pressure melting technique was used to melt zinc oxide. The ability to obtain molten ZnO enables large diameter ZnO to be crystallized using conventional melt growth techniques. High quality, 50 mm diameter crystals have been obtained using this technique. Optical and structural analysis of these crystals included x-ray

diffraction, photoluminescence spectroscopy, and electron microscopy. Temperature dependent Hall data was measured for representative crystals. Results of nitride epitaxy on ZnO bulk substrates will be presented.

4:15 PM E8.5
LOW TEMPERATURE EPITAXIAL GROWTH OF ZnO LAYER ON SAPPHIRE BY PLASMA-ASSISTED EPITAXY. Satoshi Yamauchi, Takashi Hariu, Ibaraki Univ, Dept of Systems Engineering, Ibaraki, JAPAN.

ZnO is an interesting material with high potential for blue or UV light emitting devices, transparent conducting film and SAW filters. Recently, several epitaxial growth processes have been attractively tried for high quality ZnO epitaxial growth. It has been, however, recognized that undoped-ZnO layers show oxygen-vacancies and interstitial-Zn, therefore, the use of activated oxygen species and low temperature growth should be required to get high quality ZnO layers. Plasma-assisted epitaxy (PAE), in which hydrogen gas plasma has been employed for low temperature epitaxial growth of compound semiconductors in III-V group and II-VI group. In this presentation, PAE-process for ZnO epitaxial growth on sapphire at low temperature is described together with their properties. ZnO thin films were epitaxially grown at 400°C with high growth rate around 25nm/min on C-sapphire with thin buffer layer grown at lower temperature and with low growth rate in oxygen plasma which is excited by rf-power at 13.56MHz. Photoluminescence spectra at 10K dominated by strong bandedge emission indicated oxygen vacancies in the films were almost removed by PAE-process with optimization of induced rf-power during the growth. Surface roughness and poly-crystallization in thickers than 10000nm on C-sapphire, which is caused by small probability of nucleation on the substrate, were well suppressed by employing the initial-buffer layer. These results show the PAE-process which uses oxygen-plasma is very much effective for high-quality ZnO growth and the optimization of the initial-buffer layer is very important to improve the crystallograhic and electronic properties.

SESSION E9: POSTER SESSION
WIDE BANDGAP
MATERIALS/CHARACTERIZATION/
PROCESSES/DEVICES
Chairs: Thomas E. Kazior, Chanh Nguyen, Primit Parikh and Edward T. Yu
Thursday Evening, April 19, 2001
8:00 PM
Salon 1-7 (Marriott)

E9.1
EFFECTS OF BEAM CURRENT DENSITY ON ION BEAM SYNTHESIS OF SiC. D.H. Chen, S.P. Wong, Chinese University of Hong Kong, Department of Electronic Engineering and Materials Science & Technology Research Centre, HONG KONG, CHINA; J.K.N. Lindner, Universität Augsburg, Institut für Physik, Augsburg, GERMANY.

Thin SiC layers were synthesized by high dose C implantation into silicon using a metal vapor vacuum arc ion source at various conditions. Characterization of the ion beam synthesized SiC layers was performed using various techniques including x-ray photoelectron spectroscopy (XPS), Rutherford backscattering spectrometry (RBS), transmission electron microscopy (TEM), Fourier transform infrared (FTIR) absorption, and Raman spectroscopy. The XPS and RBS results showed that for samples with over-stoichiometric implant doses, if the implant beam current density was not high enough, even after prolonged thermal annealing at high temperatures, the as-implanted gaussian-like carbon depth profile remained unchanged. However, if the implant beam current density was sufficiently high, there was significant carbon redistribution during annealing, so that a thicker stoichiometric SiC layer can be formed after annealing. The XPS and Raman results also showed that while there were carbon clusters formed in the as-implanted layers for the low beam current density implanted samples the formation of such carbon clusters was minimal in the high beam current density as-implanted samples. The effect of beam current density on the fraction of different bonding states of the implanted carbon atoms was studied and their consequences to other properties of the SiC layers were discussed in conjunction with the results of other characterization techniques. This work is partially supported by the Hong Kong-Germany joint research scheme. One of us (DHC) is supported by a Postdoctoral Fellowship from the Faculty of Engineering, CUHK.

E9.2
CHARACTERIZATION OF P-TYPE 4H-SiC EPITAXIAL LAYER GROWN ON (112-0) SUBSTRATE. Kazutoishi Kojima, Toshiyuki Ohno, Mituhiro Kushibe, Koh Masahara, Takaya, Suzuki and Tomoyuki Tanaka, R&D Association for Future Electon Devices, Ibaraki, JAPAN; Yuuki Ishida, Tetuo Takahashi and Kazuo Arai, Electrotechnical Laboratory, Ibaraki, JAPAN.

Recently, high channel mobility was realized on n-channel planar MOSFETs fabricated on p-type 4H-SiC (112-0) epilayer. However, few investigations for p-type 4H-SiC (112-0) epitaxial layer were reported. In this study, We have characterized the Al doped p-type 4H-SiC epitaxial layers on (112-0) substrates grown by low-pressure, hot wall type CVD reactor with SiH4 - C3H8 - H2 - TMA system. The doping concentration range from about 1x1016 cm-3 to 1x1019 cm-3 was obtained by controlling of TMA flow rate. In this range, the (112-0) epilayers exhibited higher doping concentration than conventional off-angle (0001) epilayers. In low-temperature (4.2 K) photoluminescence measurement, zero phonon spectrum of the neutral aluminum acceptor was observed. At low doping concentration, peaks due to the neutral nitrogen donor bound excitons were also observed. These nitrogen related peaks, however, decreased with increasing doping concentration and disappeared at the concentration of 1x1017 cm-3. On the contrary, the broad peak due to Aluminum related donor-acceptor pair was not observed at this doping concentration. These results indicate high quality p-type epilayers are realized. Hall effect measurements at room temperature were also carried out by van der Pauw method. The hole mobility of 65 cm2/Vs was obtained at the doping concentration of 9x1016 cm-3. The mobility increased with decreasing doping concentration and reached 73cm2/Vs at the doping concentration of 7x1015cm-3. On the other hand, the hole mobility of (0001) epilayer at the doping concentration of 4x1015cm-3 was 68 cm2/Vs. These results indicate the hole mobility of (112-0) epilayer is higher than (0001) epilayer at the same doping concentration level. They also suggests there exists the hole mobility anisotropy between the directions parallel and perpendicular to [0001] axis. This study was performed the management of FED as a part of the MITI NSS Program supported by NEDO of Japan.

E9.3
PHOTOLUMINESCENCE PHASE-SHIFT MEASUREMENTS OF MINORITY CARRIER LIFETIMES IN SiC. Yaroslav Koshka, Michael S. Mazzola, Department of Electrical and Computer Engineering, Mississippi State University, Mississippi State, MS.

An ability to measure minority carrier lifetime is important for semiconductor device fabrication. It is also widely used as a characterization tool for monitoring incorporation of electrically active defects during material growth and device processing. Transient photoluminescence (PL) is an attractive method for minority carrier lifetime characterization because its preparation free non-contact nature, a possibility of a quick mapping of a full sample, and an easily varied spatial resolution. However, due to short values of lifetime that are typical for SiC polytypes, a very short excitation pulses (from nanoseconds to fractions of nanoseconds) are required, which dictates need in an expensive pulsed laser sources. An alternative characterization technique based on the measurement of the steady-state phase-shift between the excitation source and the detected band edge photoluminescence was used in the present work to determine the minority carrier lifetime in silicon carbide (SiC) homoepitaxial layers grown by an atmospheric pressure chemical vapor deposition. Measurements were performed at different excitation-beam power densities to determine the conditions corresponding to low- and high-excitation levels. A reduction of the apparent lifetime at high excitation typical for Auger recombination was observed. For measurements performed on relatively thin epitaxial layers (10 mm thick), the observed values of minority carrier lifetime decreased with increasing excitation wavelength. This was attributed to a high level of non-radiative recombination in the substrate and at the substrate-epilayer interface, which contributed to the PL decay at deeper light penetrations. For a 300 nm excitation wavelength corresponding to a relatively shallow light penetration, the lifetime was observed to decrease with increasing temperature. A possible mechanism for the temperature dependence as well as errors introduced by recombination in the substrate and at the surface are discussed.

E9.4
PHOTO ESR STUDY OF TRAPPING AND RECOMBINATION PROCESSES IN SEMI-INSULATING 4H-SiC CRYSTALS AS FUNCTION OF TEMPERATURE. E.N. Kalabukhova, S.N. Lukin, Institute of Semiconductor Physics, NASU, Kiev, UKRAINE; A. Saxler, Cree Inc, Durham, NC; W.C. Mitchel, S R. Smith, and J.S. Solomon, Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, OH; A.O. Evwaraye, University of Dayton, Physics Department, Dayton, OH.

Measurements of the ESR spectrum of semi-insulating (s.-i.) 4H SiC have been made at 37 GHz as a function of illumination wavelength and temperature. At T= 77 K in the dark the ESR spectrum consists of a low intensity line due to boron on the cubic lattice site and single

line with isotropic $g_{\|} = g_{\perp} = 2.0025$. During illumination with ultraviolet light the lines due to boron on the hexagonal and nitrogen on the cubic site appear and persist after the illumination is remove. During and after illumination with sub-band gap, visible, light a fifth line, I_{P1}, appears with $g_{\|} = 2.0048$ and $g_{\perp} = 2.0030$. Studies of the wavelength dependence of I_{P1} suggest that it is due to the as yet unidentified deep level located at E_C - 1.1 eV which pins the Fermi level in this sample at 77 K. A model for trapping and recombination (TR) process without detectable concentrations of vanadium is presented. The temperature behavior of photo-excitation ESR spectrum was shown that at higher temperature (77 K) the photocreated carriers are mainly captured by the midgap I_{P1} center with energy level E_C - 1.1 eV and nitrogen, boron on cubic sites having more deeper levels in band gap. When the temperature decrease the capture of free carriers by shallow donor and acceptor becomes more efficient and additional I_D ESR line with $g_{\perp}$ =2.0006 due to second shallow donor state appears after illumination the sample with above band gap light. At T=4.2 K the photo-excitation ESR spectrum consists only of I_D and boron ESR line on hexagonal site having more shallower levels in band gap. Two quasi Fermi levels could be applicable to explain the temperature behavior of TR processes in s.-i. 4H SiC samples.

E9.5
HIGH QUALITY GaN EPILAYER GROWN BY RF PLASMA ASSISTED MBE ON INTERMEDIATE-TEMPERATURE GaN BUFFER LAYER. W.K. Fong, C.F. Zhu, B.H. Leung, C. Surya, The Hong Kong Polytechnic University, Department of Electronic and Information Engineering, HONG KONG.

High quality GaN thin films were grown by rf-plasma assisted molecular beam epitaxy on intermediate-temperature buffer layer (ITBL). The results showed a systematic change in both electrical and optical properties by varying the thickness of ITBL. Room temperature electron mobility increased steadily from 87 $cm^2V^{-1}s^{-1}$, for film grown with just 20 nm low-temperature (LT) buffer layer, to 377 $cm^2V^{-1}s^{-1}$ for sample grown with an 800-nm-thick ITBL inserted between the 20 nm LT buffer layer and the epilayer. Photoluminescence (PL) spectra also demonstrated a systematic increase in the luminescence intensity and a reduction in full width at half maximum of the near band-edge emission in presence of ITBL. Our analyses of the mobility and PL results demonstrated that the utilization of an ITBL in addition to the conventional LT buffer layer led to the relaxation of residual strain and the optimal thickness of ITBL was found to be 800 nm. Electron mobility as high as 430 $cm^2V^{-1}s^{-1}$ is obtained from the sample grown on a 800 nm ITBL on top of a 40 nm low-temperature buffer layer.

E9.6
EFFECT OF V/III FLUX RATIO ON GROWTH TEMPERATURE FOR InGaN/GaN MQW STRUCTURES GROWN BY MOCVD. Rakjun Choi, Kisoo Kim, Chisun Kim, Myunggoo Cheong, Youngkyu Hong, Hosnag Yoon, Changhee Hong, Yoonbong Hahn, Hyungjae Lee, Chonbuk Univ, Semiconductor Physics Research Center, Chonju, KOREA.

Group III nitrides have attracted much attention in applications of visible light emitting diodes and violet laser diodes because of their band gap and the wavelength tunability from red into UV regions. But there still remain problems related to the epitaxial growth of $In_xGa_{1-x}N$ alloy. This can be attributed primarily to the characteristics of a low decomposition efficiency of ammonia, high In desorption rate, which are strong dependence of growth temperature. First, we carried out a systematic study varying ammonia flow rate with constant In flow rate and growth temperature. Second, we carried out varying In flow rate with constant ammonia flow rate and growth temperature. The optical and structure properties of InGaN/GaN multi-quantum well (MQW) structures were examined by photoluminescence (PL), atomic force microscopy (AFM), high resolution transmission electron microscopy (HRTEM), high resolution X-ray diffraction (HRXRD). The results was found to the formation of In composition fluctuation if a relatively low V/III ratio, that is, a suitable amount of activated N is not present on the surface of the growing layer, whereas if the group V source is supplied in excess, radiative process decreased due to increase of In desorption rate and concentration of contaminates. The growth mechanism of $In_xGa_{1-x}N$ alloy was found to be sensitive to the ammonia flow rate with relatively low In mole fraction rather than high In mole fraction at constant growth temperature. Therefore, to obtain a high quality of $In_xGa_{1-x}N$ alloy must be considered ammonia flow rate, In flow rate, and growth temperature together.

E9.7
SINGLE DOMAIN STRUCTURE OF 2H-AlN FILMS ON Si(001) SUBSTRATES. Joerg Jinschek, Vadim Lebedev, Ute Kaiser, Wolfgang Richter, Institute for Solid State Physics, Friedrich-Schiller University of Jena, Jena, GERMANY.

By conventional and high resolution transmission electron microscopy (TEM) investigations on 2H-AlN films grown by plasma-assisted molecular beam epitaxy (MBE) on Si(001) the influence of the off-axis angle of the substrate surface on the film structure was studied. Three types of Si(001) substrates were used: on-axis, $\sim 1°$, and $\sim 5°$ off-axis Si(001) substrates. The 2H-AlN layer on an exact oriented Si(001) substrates consists of 3 AlN film domains: two main film domains, AlN_1 and AlN_2, and a small domain AlN_3 at substrate surface defects. Their c-axis orientations are parallel to the c-axis of the substrate: $[0001]AlN_{1,2,3} \parallel [001]Si$. The a-axes of AlN_1 and AlN_2 rotated by 30° to each other: $[11\bar{2}0]AlN_1 \parallel [01\bar{1}0]AlN_2 \parallel [1\bar{1}0]Si$. The a-axis orientation of AlN_3 is $[01\bar{1}0]AlN_3 \parallel [100]Si$. In 2H-AlN films grown on off-axis Si(01) substrates ($\sim 1°$ and $\sim 5°$) the ratio between the AlN_1 and AlN_2 film domains changes dramatically as far as a single domain film structure consisting of only AlN_1 is reached. The AlN c-axes of all domains on the off-axis substrates are not parallel to the Si c-axis but tilted by the off-axis angle of the Si(001) substrate ($\sim 1°$ respectively $\sim 5°$), i.e. [0001]AlN is parallel to the Si(001) substrate surface orientation. Determination of the AlN_1 domain / Si(001) interface structure by high resolution TEM illuminates the origin of the preference of this domain in the 2H-AlN film by using off-axis Si(001) substrates. On the on-axis substrate a regular array of misfit dislocations causes a 5:4 fit between the $(1\bar{1}00)$AlN and $(\bar{1}\bar{1}0)$Si lattice planes. The off-axis Si(001) leads to a rotation of the AlN lattice in respect of the Si lattice. An array of misfit dislocations with a 4:3 fit between $(1\bar{1}01)$AlN and $(\bar{1}\bar{1}1)$Si lattice planes decreases the residual lattice misfit from -1.3% to -0.8%.

E9.8
RAMAN SCATTERING SPECTRA IN C-IMPLANTED GaN EPILAYERS. W.H. Sun, S.J. Chua, Institute of Material Research and Engineering, SINGAPORE; K.M. Chen, G.G. Qin, Department of Physics, Peking University, Beijing, CHINA.

We have investigated the Raman scattering spectra in C-implanted GaN epilayers. (a) In as-implanted GaN, new Raman bands at 293, 376, 669, 1027, 1094 and 1053cm^{-1} appeared. From phonon-dispersion curves for hexagonal GaN, the 293 and 669 cm^{-1} bands were assigned to the highest acoustic-phonon branch and the optical-phonon branch at the Brillouin zone boundaries, respectively, which can be explained by disorder-activated Raman Scattering induced by implantation; the 1027 and 1094 cm^{-1} peaks may be caused by two-phonon scattering involving the 376 and 669 cm^{-1} phonons, and the 376 cm^{-1} and A1(LO) phonons respectively.(b) Two sharp bands at 1350 and 1600 cm^{-1} were observed in the Raman spectra of carbon-implanted GaN after post-implantation annealing treatments. The intensities of these two bands increased while their full widths at half maximum decreased with increasing annealing temperature. We assigned them, respectively, to the D and G bands of small graphite crystallites arising from C implantation and post-implantation annealing. The observation of these two bands indicates the formation of small graphite crystallites in C-implanted GaN.

E9.9
COMBINED UV RAMAN SCATTERING AND PHOTO-LUMINESCENCE OF GaN AND RELATED MATERIALS ON SAPPHIRE. Zhe Chuan Feng, Wei Wang, Soo Jin Chua, Institute of Material Science & Engineering, SINGAPORE; Ken P.J. Williams, G. David Pitt, Renishaw plc, UNITED KINGDOM.

Micro-Raman scattering and micro-photoluminescence spectroscopy under excitation of ultraviolet (UV) 325 nm from a He-Cd laser have been employed to study GaN and related materials grown on sapphire substrates by low-pressure metalorganic chemical vapor deposition (MOCVD). A variety of GaN thin film materials, un-doped, Si- and Mg-doped, and InGaN/GaN/sapphire structures were investigated. By help of a newly designed and developed UV Raman-PL microscope system, combined Raman and PL spectra can been obtained from same runs at room temperature (RT) measurements. A series of interesting results are obtained. For n-type GaN films, with increasing the SiH4 flow, RT PL of GaN band edge emission showed variations: PL peak has a slight blue-shift first and then turns to a red shift, band width decreases first and then increases, peak intensity also increases first and then decrease. We have used the bandgap renormalization due to the many-body effects and the potential fluctuations caused by the random distribution of doping atoms to explain these interesting trends. Combined UV RS-PL spectra from p-type GaN are investigated. PL characteristics from GaN band-to-band and Mg-related transitions are conveniently distinguished. Competition between the Mg-related 2.8-3.2 eV PL bands is revealed with different Mg-doping levels. Multiple Raman LO (up to 5LO) resonant modes are exhibited, which is due to the outgoing resonance with the fundamental GaN band gap. We have also observed extra phonon modes, which may be related to the p-type doped impurities. Similar combined UV RS-PL spectra and resonance enhancement of multiple LO modes from InGaN/GaN/sapphire structures are also obtained.

They are varied with the indium composition. These fruitful results demonstrate the capabilities of UV micro-RS-PL technology for the research and development of GaN and other wide bandgap materials.

E9.10
PHOTOLUMINESCENCE AND RAMAN SPECTRA OF FLUX PROCESSED BULK SINGLE CRYSTAL GaN. Chae Ryong Cho[a], Sang Eon Park[a,b], Yong Chan Cho[a,b], Se-Young Jeong[b]; [a]COMTECS Ltd, Research Laboratory, Taegu, KOREA; [b]Pusan National Univ, Dept of Physics, Pusan, KOREA.

We report the results of photoluminescence and Raman spectroscopy measurements for bulk single crystals of wurtzite GaN. The variation of full-width at half-maximum(FWHM) of rocking curve was investigated for GaN single crystal with a size of about 2 mm in length, which was grown by the flux method. The structural and compositional properties of the GaN bulk single crystal were also studied by XRD, AES and XPS techniques. The photoluminescence(PL) peak of near band-to-band transition at 365.5 nm and the E_2(high energy, 568 cm^{-1}) and A_1(LO, 737 cm^{-1}) Raman phonon modes have been obtained over a wide range of temperatures, respectively. An ultraviolet(UV) band with a zero phonon line at near 3.27 eV followed by several LO phonon replica in the low temperature was discussed. The A_1(LO) mode in the GaN allowed in the backscattering geometry was obtained and sharp line shape for the E_2 mode is considered to be due to the high crystalline quality of the crystal.

E9.11
ION BEAM SYNTHESIS OF CARBON RELATED PHASES IN SILICON CARBIDE AND DIAMOND: A NEW APPROACH TO N-DOPED DIAMOND LAYERS? W. Skorupa[a], B. Pecs[b], L. Dobos[b] and V. Heera[a]; [a]Institute of Ion Beam Physics and Materials Research, Forschungszentrum Rossendorf, Dresden, GERMANY; [b]Research Institute for Technical Physics and Materials Science, Budapest, HUNGARY.

Ion beam synthesis (IBS) is a versatile instrument to circumvent obstacles dictated by the thermal equilibrium. The basic steps to perform ion beam synthesis include ion beam irradiation with stoichiometric doses into a target kept at a certain temperature followed by another dedicated annealing step. It is just its closed combination with thermal processing why IBS-based processing can result in even more surprising effects. In this paper we will demonstrate at first, that high dose carbon implantation into silicon carbide leads to the formation of three different carbon-related phases dependent on the target temperature during the ion beam irradiation: an amorphous, carbon rich phase at 300°C, graphite at 600°C, and diamond at 900°C. In the latter case the grains are in perfect epitaxial relation with the surrounding 6H-SiC lattice. At second, it will be shown that high dose silicon implantation into natural diamond at 900°C favors the formation of 3C-SiC grains in diamond with perfect epitaxial relation to the diamond lattice. Using an additional nitrogen implantation step into this layer arrangememt, electrial measurements showed a distinct conductivity increase pointing to n-type doping of the SiC grains embedded into the diamond lattice.

E9.12
EFFECT OF AN OXIDIZED Ni/Au P-CONTACT ON THE PERFORMANCE OF GaN/InGaN MULTIPLE QUANTUM WELL LIGHT-EMITTING DIODES. Hyunsoo Kim, Seong-Ju Park, and Hyunsang Hwang, KJIST, Materials Science Dept., Kwangju, KOREA.

In order to improve the performance of GaN-based light emitting diode (LED), low resistance ohmic contacts on both n- and p-type GaN are essential. In addition, obtaining highly transparent current spreading layer in the visible region is very important in order to maximize the extraction efficiency of the generated light. For these requirements, highly transparent indium tin oxide (ITO) and Pt thin films have been successfully demonstrated for the GaN-based LED as a p-type current spreading layer. Recently, Ho et al. reported a breakthrough in the Ni/Au system which involved an oxidation process and which resulted in the specific contact resistances as low as 4.0 x 10^{-6} Ω-cm^2, and a high light transparency of 80%in the 450-550 nm wavelength region. From this point of view, we investigated feasibility of an oxidized Ni/Au p-contact on some aspects of device applications for a GaN/InGaN multiple quantum well (MQW) LED. For the oxidation of Ni/Au p-contact, furnace annealing of a completely fabricated LED was performed at 600°C for 5 min in an O_2 ambient. For the case of LED with an oxidized Ni/Au system, the I-V measurements showed a reduction in series resistance of the diode by 17.2%. In addition, the optical output power of the oxidized LED was increased by a factor of 2. However, a significant degradation in reliability characteristics was observed, which might detract from the direct application of the Ni/Au oxidation process. We also found that the improvement of oxidized Ni/Au contact properties is mainly due to the formation of an intermediate NiO layer, rather than an enhancement in p-type activation.

E9.13
A THEORETICAL MODEL AND COMPUTER SIMULATION OF FLICKER NOISE IN GaN/AlGaN HFETs. Dmitri Kochetkov and Alexander Balandin, Univ of California - Riverside, Dept of Electrical Engineering, Riverside, CA.

Investigation of flicker noise in GaN/AlGaN heterostructure field-effect transistors (HFETs) has recently attracted a lot of attention. This is due to a demonstrated potential of GaN HFETs for high-power density and high frequency applications. It has been experimentally shown [1] that (i) Hooge parameter in these devices may vary for several orders of magnitude in similar devices, (ii) the noise spectral density deviates significantly from the 1/f law and (iii) strongly depends on the applied bias. All these result in an apparent inability to describe the noise in GaN transistors with the analytical models developed for conventional devices such as Si CMOS transistors. In this talk we will present our theoretical model of flicker noise in GaN HFETs. We will show that computer simulation results are in good agreement with the experimentally observed noise spectra and their bias dependence [1]. The model also correctly predicts the linear dependence of g parameter on the applied gate bias. Our theoretical formalism is based on the modified carrier tunneling mechanism and takes into account spatial and energy non-uniformity of trap distribution. Materials and device parameters characteristic for GaN HFETs have been included into the model. By fitting theoretical spectra to experimental results we have been able to determine the trap distribution profile, tunneling length and other microscopic material parameters. The model can be easily incorporated into commercial device simulation software. [1]. Balandin, A., S. Morozov, S. Cai, R. Li, K.L. Wang, C.R. Viswanathan, IEEE Trans on Microwave Theory & Tech, 47:1413-1417 (1999).

E9.14
HYBRID MODEL FOR GRADED BASE III-N HETEROJUNCTION BIPOLAR TRANSISTOR. Yumin Zhang, University of Wisconsin-Platteville, Department of Electrical and Software Engineering, Platteville, WI; P. Paul Ruden, University of Minnesota, Department of Electrical and Computer Engineering, Minneapolis, MN.

This paper presents a hybrid model and simulation results for an advanced, graded base AlGaN/GaN heterojunction bipolar transistor (HBT) structure. The base of the n-p-n HBT examined has two parts, a linearly graded AlGaN layer on the emitter side and a heavily p-doped GaN layer on the collector side. In the hybrid model developed here the potential profile is first calculated self-consistently in the biased state taking into account ionized impurity charges, polarization charges, and majority carrier charges. The minority carrier transport is then examined subsequently. The injection of electrons from the emitter is modeled as a thermionic emission process. Because of the relatively wide graded region, tunneling and thermionic field emission effects are relatively unimportant. The minority electron transport process in the graded region is drift-dominated due to the large built-in effective field strength. In the low-field GaN layer of the base, electron transport is assumed to be diffusion-dominated. High-level injection effects are modeled in the framework of the Gummel-Poon model. Example structure design parameters are presented. It is found that the calculated current gain can be greater than 25, with a collector current density of 10,000 A/cm^2. This compares favorably with, both, model and experimental results for more conventional III-nitride HBT designs.

E9.15
DESIGN OF METAL-SEMICONDUCTOR-METAL ULTRA-VIOLET DETECTOR ON GALLIUM NITRIDE. Wenhua Gu, Soo Jin Chua, National Univ of Singapore, Dept of Electrical and Computer Engineering, SINGAPORE; Xin Hai Zhang, National Univ of Singapore, Institute of Material Research and Engineering, SINGAPORE.

Visible-blind UltraVioletUV detector based on GaN has been the focus of more and more intense interest in recent years, mainly because of the wide bandgap and remarkable tolerance to aggressive environments of GaN. Metal-Semiconductor -MetalMSM structure is adopted by many researchers on UV detector because of its high response speed and great potential in optical integration. But no research on how to optimize such a GaN based MSM structure has been reported. The design of GaN based MSM detector is discussed and optimized in this letter. Dimension of the special inter-digital shaped electrodes and the GaN active layer thickness are optimized by simulation using Medici. We find that these structure parameters have great impact on the response current and speed. This can be well explained by analysing the effective electric field distribution. Also we have found out an optimal structure for such detectors. The

relationship between response current and applied bias under different incident flux is also discussed. Under all incident flux, the response current tends to be saturated above 10V. When the incident flux increases, the current increases linearly, but the saturation speed is decreased, probably because of carrier screening effect.

E9.16
ALUMINUM NITRIDE (AIN) THIN FILMS FOR AW SENSORS FOR BIOLOGICAL DETECTION. Chantelle Hughes, G.W. Auner, Dept of Electrical and Computer Engineering, Wayne State University, Detroit, MI; R. Naik, Dept of Physics, Wayne State University, Detroit, MI; C. Huang, Dept of Electrical and Computer Engineering, Wayne State University, Detroit, MI; Gina Shreve, Dept of Chemical Engineering, Wayne State University, Detroit, MI.

Acoustic wave (AW) technology has been applied to the field of microelectronic sensors quite successfully. The high sensitivity of these sensors make them efficient devices for measuring gaseous compounds in extremely low concentrations. Gas sensitivity is typically achieved by coating the device surface with a thin film of a stationary phase which will selectively absorb and concentrate the target gas. The prospect of using AlN nitride thin films as a piezoelectric substrate for the SAWs is highly promising. AlN thin films possess very high phase velocity of SAW spreading, which is responsible for less SAW dispersion, a high chemical and thermal resistance and is mechanically very durable. Thin films of Aluminum nitride (AlN) were grown using the technique of plasma source molecular beam epitaxy (PSMBE). The films were grown on Al_20_3(1-102) and Al_20_3(0001) substrates. Structural characterization of the film was performed by x-ray diffraction (XRD) and high resolution electron microscopy (HREM). The XRD pattern indicates complete film texture. Cross-sectional TEM reveals epitaxy of AlN on these substrates. The Al_20_3(0001) plane is lattice matched to the c-plane growth of AlN and the Al_20_3(1-102) plane is lattice matched to the a-plane growth of AlN. A shear opto-acoustic wave sensing platform has been developed from the AlN films. The device has an integrated laser diode with high frequency modulation hybrid to the chip. The laser diode pulses light in an AlN waveguide to an array of acoustic wave devices. The laser light absorbs at the carbon implanted region generating an acoustic shear wave. The design forces a preferential shear rather than SAW wave to form and is an important and unique feature of the device. An immobilization layer containing chemical or biological binding sites transverses the resonating bridge. Interaction by an analyte containing target molecules or structures will bind to this area of the device and change the resonate frequency. The thin AlN crystal bridge vibrates at a frequency of f. Analyte binding to the surface causes a frequency change Δf equal to -2.3 $\times 10^6$ f^2 $\Delta M/A$ where f is the frequency in MHz, ΔM the mass in gms deposited on the surface, and A the area in cm^2. A prototype online sensor for real time sensing and quantitation of the levels of harmful E. Coli bacteria will be presented. The device uses a monoclonal antibody, immobilized to the AW device, that binds specifically with the E. Coli pilus. This antibody possesses high specificity for pili associated bacteria.

E9.17
DEVELOPMENT OF AlN THIN FILM BASED PIEZOELECTRIC SENSORS FOR ULTRASONIC IMAGING. Marvie Nickola, Greg Auner, Changhe Huang, Department of Electrical and Computer Engineering, Wayne State University, Detroit, MI; Ratna Naik, Department of Physics, Wayne State University, Detroit, MI; Vaman Naik, Dept. of Natural Science, Univ of Michigan-Dearborn, Dearborn, MI.

The piezoelectric properties of AlN thin films have been of practical interest for many acoustic wave sensor application. In the present study, AlN thin films ($\sim 1\mu m$) have been grown by plasma source molecular beam epitaxy (PSMBE) on Si and sapphire substrates. Both x-ray diffraction and optical studies confirm high quality of AlN thin films. Excimer laser (KrF) micromachining has been used to fabricate (4x4) pixulated array of AlN piezoelectric sensors. The results of ultrasonic wave imaging using a 5 MHz ultrasonic wave will be presented to investigate the effect of size and geometry of pixels.

E9.18
DEVELOPMENT OF WIDE BAND GAP SEMICONDUCTOR WAVEGUIDE FOR MICROFLUIDIC DRUG DELIVERY. Mona Safadi, Greg Auner, Changhe Huang, Vaman Naik, Wayne State University, Dept of Electrical and Computer Engineering, Detroit, MI; Ratna Naik, Wayne State University, Dept of Physics, Detroit, MI.

The development of an Excimer laser (KrF) micromachined micro-fluidic device using AlN thin films that allows us to deliver caged compounds to the retina or brain is reported. Integrated within the device is an array of fiber optic light pipes. These allow for the spatially structured delivery of ultraviolet light (260 nm) needed for the activation of the caged neurotransmitters. Single crystal AlN thin films are grown on SiC, Si and sapphire with high refractive index buffer layer by plasma source molecular beam epitaxy (PSMBE). KrF Excimer laser micromachining technology is employed to micro-fabricate wave-guiding channels for the input light beam and diffracted light beams onto the AlN thin film. Wave-guiding channels are precisely fabricated to form a cavity to maximize the intensity of UV light. Wave-guide properties are characterized as a function of film thickness, geometry and crystalline quality. Results of a prototype microfluidic waveguide system will be presented.

E9.19
DEFECTS IN 4H-SiC INDUCED BY HIGH ENERGY HELIUM IMPLANTATION. P.O. Renault, M.F. Beaufort, E. Oliviero, M.L. David, A. Declémy, C. Blanchard, J.F. Barbot, LMP UMR CNRS, Université de Poitiers, Futuroscope, FRANCE; E. Ntsoenzok, CERI CNRS, Orl'eans, FRANCE.

Nanocavities created by helium implantation are expected to play an important role in semiconductor devices, like gettering of unwanted impurities. In this way, helium ions have been implanted in crystalline n-type 4H-SiC at 1.6 MeV and dose of 10^{17} cm^{-2} using a Van de Graaff accelerator. Cross-sectional TEM have been performed to study the as-induced defects. In the as-implanted sample, a continuous damage layer of 630 nm width is observed. This layer is made up of three different regions. The central part is an amorphous area with a dense population of small bubbles (1-2 nm in diameter). The two outside layers contain mainly small clusters of point defects which were impossible to solve using conventional microscopy (TEM). HRTEM experiments in these regions also show numerous stacking faults perpendicular to the [0001] direction. After a 30 min annealing at 1500°C, the amorphous part is completely recrystallized in different polytypes: 4H-SiC along the c-direction from the substrate columnar 4H-Sic and epitaxial 3C-SiC. Inside this central layer, many bubbles are also observed. These bubbles show different sizes ranging from 5 to 50 nm and different shapes (cylindrical, circular, faceted) which depend on their position in the band. After annealing, the outside regions show a smaller density of defects. Moreover, we observe the spread out toward the surface of the above region. Further experiments are in progress.

E9.20
COPPER OHMIC CONTACTS TO n-TYPE SiC FORMED WITH PULSED EXCIMER LASER IRRADIATION. K. Abe, M. Sumitomo, O. Eryu, and K. Nakashima, Department of Electrical and Computer Engineering, Nagoya Institute of Technology, Gokiso, Showa, Nagoya, JAPAN.

Ohmic contacts to SiC is usually formed by annealing at high temperature ranging from 700 to 1000°C. We have proposed that the pulsed laser process was a suitable method for the fabrication of ohmic contacts to SiC and for the impurity doping into SiC at room temperature [1,2]. In this study, Cu ohmic contacts to n-type SiC were fabricated with pulsed excimer laser irradiation. Cu is a promising metal for metallizations due to its lower resistivity than Al and Ni, widely used to form ohmic contacts to SiC (1.6 $\mu\Omega$·cm for Cu, 2.5 $\mu\Omega$·cm for Al and 6.2 $\mu\Omega$·cm for Ni). These experiments were performed using n-type bulk 6H-SiC (0001) Si-face with a net donor concentration of $1.5x10^{18}/cm^3$. Cu-films 25±5 nm thick were deposited with thermal evaporation onto the substrate. The metal-deposited layers were irradiated with pulsed KrF excimer laser (248 nm) at various energy densities in N_2 flow. Subsequently, Au overlayers were deposited to prevent oxidation of Cu contacts. The energy density above $1.1J/cm^2$ yielded ohmic behavior and these contacts had a smooth surface (roughness average: R_a = 3.5 nm). The properties of contacts layers were characterized using current-voltage (I-V) measurements, secondary ion mass spectroscopy (SIMS), and Auger electron spectroscopy (AES).
[1] K. Nakashima, O. Eryu, S. Ukai, K. Yoshida and M. Watanabe, Materials Science Forum, **338-342**, 1005 (2000).
[2] O. Eryu, Y. Okuyama, K. Nakashima, T. Nakata, M. Watanabe, Appl. Phys. Lett., **67**, 2052 (1995).

E9.21
AB-INITIO CALCULATION OF THE β-SiC/Ni INTERFACE. A. Blasetti, G. Profeta, S. Picozzi, A. Continenza, Dip. Fisica, Univ. L'Aquila, Coppito, L'Aquila, ITALY; A.J. Freeman, Dept. of Phys. and Astron., Northwestern Univ., Evanston, IL.

Recent progress in SiC-based technology has raised interest in possible applications of this material in devices exploiting high temperature metal contacts. Within this framework, Ni plays an important role; in fact, the "as deposited" SiC/Ni interface shows a rectifying behavior, while it exhibits ohmic behavior after annealing, probably related to the formation of silicides or carbides. In order to understand the stability of the SiC/Ni interface and its electronic properties, we performed an ab–initio study using the full–potential linearized augmented plane wave (FLAPW) method[1]. We study both the Si- and C-terminated junction and, for each termination, we focus

on the structural properties analyzing interface bond lengths, strain effects and atomic buckling. Our results for the adhesion energy clearly show the strong reactivity of this interface and give a rationale for its high thermal stability. Finally, we study behavior of the metal induced gap states (MIGS), the dependence of the Schottky barrier height on the termination and investigate the role of SiC ionicity in the formation of the barrier.

[1]H.J.F. Jansen and A.J. Freeman, Phys. Rev. B **30**, 561 (1984).

E9.22

Ni-Si CO-IMPLANTATION INTO SiC TO FORM OHMIC CONTACT. Abdalla Elsamadicy[a], D. Ila[a], R. Zimmerman[a], D.B. Poker[b], D. Hensley[b]; [a]Center for Irradiation of Materials, Alabama A&M University, Normal, AL; [b]Solid State Division, Oak Ridge National Laboratory, Oak Ridge, TN.

We have co-implanted Ni and Si into 6H-SiC in order to form Nickel Silicide (Ni_2 Si)compound at shallow depth. We used this compound layer to assist formation of an improved Ohmic contact with the SiC substrate. The Nickel Silicide layer was formed by implanting Ni and Si ions at low energies and with various fluencies in both Si and C faces of the SiC substrate, with different substrate temperatures. I-V characteristics and surface contact resistance at each annealing temperature were studied from 100°C to 700°C. Rutherford Backscattering Spectroscopy (RBS) and Auger Electron Spectroscopy (AES) were used for depth profiling of the (Ni_2 Si), Si, and C. X-ray Photoemission Spectroscopy (XPS) was used to study the chemical structure of the (Ni_2 Si)/SiC interface. Research sponsored in part by the NASA-Alabama Space Grant Consortium, Ctr. for Irradiation of Materials of Alabama A&M University and by the U. S. Department of Energy under contract DE-AC05-00OR22725 with the Oak Ridge National Laboratory, managed by UT-Battelle, LLC.

E9.23

ION IMPLANTED MESFET TECHNOLOGY IN 4H SiC. Alton Horsfall, Mark Johnson, Nick Wright, University of Newcastle, Dept. of Electrical and Electronic Engineering, Newcastle, UNITED KINGDOM.

An ion implanted MESFET structure in 4H SiC is presented. The device is fabricated in an n-type 3E15 cm^{-3} epitaxial layer by boron implantation to form the p-well and nitrogen implantation for the channel. The channel is doped at 1.5E18 cm^{-3} with a depth of 0.15um, which is designed to be reduced by etch optimization in the fabrication process. It is well known that the electrical characteristics of implanted SiC are dependant on the annealing strategy and a dual implant and anneal technique has been shown to be favourable for these devices. This allows two differing anneal temperatures to be used: a high temperature anneal for the boron p-well giving high dopant activation and a low temperature anneal of the subsequent nitrogen implant which helps to reduce the surface roughness. The lower anneal temperature of the channel implant also helps to maintain a higher carrier mobility and values of $50cm^2/(Vs)$ have been recorded with a 1300C anneal compared to $5cm^2/(Vs)$ for the 1600C one step technique. Further results show that the preparation of the surface and pre-deposition clean for the Schottky gate contact are critical steps in determining device performance. Electrical characteristics, taken at temperatures between 300K and 600K will also be presented and discussed.

E9.24

IMPROVED VOLTAGE-BLOCKING CAPABILITY OF THE SiC DISTRIBUTED BUFFER GATE TURN-OFF (DB-GTO) THYRISTOR STRUCTURE. P.B. Shah, B.R. Geil and K.A. Jones, U.S. Army Research Laboratory, Adelphi, MD.

Drift-diffusion simulations demonstrate that with additional higher doped buffer layers in the drift region forming a $pn-pn-pn$-type device, the SiC DB-GTO thyristors' breakover voltage, V_{BR}, increases. These layers move the electrostatic field peak away from sharp corners and the passivation oxide. The drift region contains $p-/n-$buffer/$p-$layers referred to as 1, 2, and 3 from top to bottom. The devices are isolated with a 0.5μm-deep etch into region 1. Typical material parameters were used. For the anode and gate regions, however, lower mobilities and carrier lifetimes (μ_n = 25-cm^2/V/s, μ_p = 20, and $\tau_n = \tau_p$ = 20ns) were used. This was done because simulations of a reported structure with these parameters gave a quasi-static turn-off gain, K_{Gst} = 7.45 for switching 1 kA/cm^2, and an on-state voltage drop of 7.9V compared to the reported value of K_{Gst} = 6 and 6.5V. The use of typical ideal material parameters gave much lower turn-off gains and on-state voltage drops than measured. Without field terminations, a 15μm drift region DB-GTO thyristor structure blocks 2211V and has a stairstep drift-region electrostatic-field profile. A 15μm drift region structure without the $n-$buffer layer blocks 757V. The DB-GTO thyristor's maximum electrostatic field is between regions 2 and 3 rather than at the top of region 1 in the conventional structure. The location, concentration, and thickness of the $n-$buffer can be optimized. Considering device isolation, near the bottom of the $n-$buffer, the vertical current drops to 20% of its maximum 10μm from the center of the anode finger, and drops to 10% 20μm from the center. As V_{BR} increases from 2.2 to 6.7 kV, the on-state voltage drop increases at an increasing rate. The holding current also increases from 18 A/cm^2 (region 3 thickness = 31.5 μm), to 25 A/cm^2 (47.5 μm), and finally to 30 A/cm^2 (63.5 μm).

SESSION E10: GaN AND SiC DEVICES
Chair: Primit Parikh
Friday Morning, April 20, 2001
Salon 1/2 (Marriott)

8:30 AM *E10.1

NPN AND PNP BIPOLAR TRANSISTORS IN THE GALLIUM NITRIDE SYSTEM. Umesh Mishra, L. McCarthy, H. Xing, D. Green, J. Limb, I.P. Smorchkova, P. Fini, S. Keller, J. Speck, S. DenBaars, College of Engineering, UCSB, Santa Barbara, CA; Primit Parikh, J. Ibbetson, P. Kozodoy, P. Chavarkar, Cree Lighting Company, Goleta, CA.

Bipolar transistors in conventional technologies have found their niche in mixed signal ICs because of their ease of layout and precision of threshold voltage. In the power amplifier arena, they have prospered because of their normally off character, high power density, high linearity and low phase noise. It is this latter property that has fueled the interest in bipolar transistors in the GaN system. Work at UCSB has concentrated on the Npn system whereas work at CREE Lighting has focused on the pnp system. The advantage of the N(AlGaN)/p(GaN)/n(GaN) system is the combination of high power (provided by the high breakdown voltage in the GaN collector) and high speed (provided by the high electron velocity in the GaN collector). Theoretical predictions promise an fT of over 30 GHz from devices with a breakdown voltage of 100V. The problems with the Npn system are realated to the p-type base. When using MOCVD as a growth technique we have observed memory/diffusion effects of the Mg which causes the Emitter-base junction to be placed in the wide bandgap emitter. This of course results in homojunction transistors rather than the desired heterojunction transistors. By using selective area regrowth of the emitter to mitigate junction placement problems and also etching difficulties in accessing the ultra-thin base, we have achieved a beta of 10 at 300K at a current density $\sim$1kAcm^{-2}. We have also shown that p-n junction collector diodes can exhibit a breakdown voltage of over 400V. Problems with minority carrier lifetime in the base, poor base sheet resistance and poor base contact resistance continue to hurt performance. Nevertheless, we have demonstrated a current gain cut-off frequency of 2GHz , the first RF results in this material system. The pnp system in GaN is extremely attractive because the issues of base resistance vanish because of the n-type base. The determinant of device performance is now, the hole diffusion constant in the base, hole velocity in the collector and the contact resistance to the p-type emitter and collector regions. Initial results show a beta of between 10 and 50 though an accurate determination at high current densities was not possible because of current instability. In this talk current performance of both devices will be presented and the path taken to achieve the results explained.

9:00 AM E10.2

GaN AND AlGaN POWER RECTIFIERS ON SAPPHIRE AND BULK GaN SUBSTRATES. J.W. Johnson, A.P. Zhang, G.T. Dang, F. Ren, University of Florida, Dept. of Chemical Engineering, Gainesville, FL; S.S. Park and K.Y. Lee, Samsung Advanced Institute of Technology, Suwon, KOREA; J. Han, Sandia National Laboratories, Albuquerque, NM; A.Y. Polyakov, N.B. Smirnov, A.V. Govorkov, Institute of Rare Metals, Moscow, RUSSIA; J.M. Redwing, Pennsylvania State University, Dept. of Materials Science and Engineering, State College, PA; K.P. Lee, S.J. Pearton, University of Florida, Dept. of Material Science and Engineering, Gainesville, FL.

Lateral geometry AlGaN Schottky rectifiers were fabricated with Al content of 0, 0.05, 0.15, and 0.25. The 3 μm GaN and 2.5 μm AlGaN insulating layers were grown on c-Al_2O_3 substrates by metalorganic chemical vapor deposition (MOCVD). Guard rings were formed by implantation of Mg^+. The structures were capped with 600nm of PECVD-SiO_2 for surface passivation and the Schottky metal was overlayed laterally 5μm onto the dielectric to reduce field-crowding along the contact periphery. Such edge termination techniques were crucial to the attainment of high blocking voltages in these lateral devices. The reverse breakdown voltage (V_{RB}) increased with the spacing between Schottky and ohmic metal contacts. Maximum V_{RB} values of 6350V and 9700V were measured for GaN and $Al_{0.25}Ga_{0.75}N$ rectifiers, respectively, with 100 μm spacing between the Schottky contact and ohmic contact ring. These are the highest reverse breakdown voltages ever reported for rectifiers from this material system. In addition, we will discuss fabrication and device

performance of vertically-depleting rectifiers on bulk GaN substrates grown by hydride vapor phase epitaxy (HVPE).

9:15 AM E10.3
POWER PERFORMANCE OF AlGaN/GaN HJFETS ON THINNED SAPPHIRE SUBSTRATES. N. Hayama, K. Kunihiro, Y. Okamoto, K. Kasahara, T. Nakayama, Y. Ohno, K. Matsunaga, H. Miyamoto, Y. Ando, and M. Kuzuhara, Photonic and Wireless Device Research Laboratories, System Devices and Fundamental Research, NEC Corporation.

AlGaN/GaN hetero-junction FETs have been developed mostly on SiC substrates because such substrates have high thermal conductivity. However, we developed similar FETs on thinned sapphire substrates. Then, we measured DC and RF performance and confirmed reduction of thermal resistance. Sapphire-substrate-thinning will enable to open up new application of low-cost GaN HJFETs with large-diameter sapphire substrates. HJFETs are made on a 2-inch-diameter, 330-μm- thick c-plane sapphire substrate with a 3-μm-thick GaN buffer layer [1]. After device fabrication, including gold plating for forming an air-bridge, the wafer was mounted on a glass plate with wax. Then, the wafer was ground to 100-μm thickness with diamond-particle-stuck disk, lapped to about 50-μm thickness, and cut into chips of 1 x 3.5 mm by diamond blade. Then, the chips were removed from the glass plate and mounted on a ceramic package. The chips showed no significant warp. The HJFETs, with a 0.9-μm gate length and 2x50-μm width FETs, showed V_T of -6 V, I_{Dmax} of 610 mA/mm, and g_{mmax} of 100 mS/mm. Electrical characteristics did not significantly change before and after the thinning process. Thermal resistance was measured from gate-leakage current under constant DC power (1 W) application. The thermal resistance of thinned chips is 20 deg/W, while that of the respective non-thinned chips is more than 60 deg/W. HJFETs with 1.2-mm gate-width on a 50-μm-thick sapphire substrate have saturation output power (P_{SAT}) of 2.2 W (1.83 W/mm) and power added efficiency (PAE) of 48% at 1.95GHz, whereas those on a thick substrate have P_{SAT} of 1.64 W (1.37 W/mm) and PAE of 47%. This peak power density is 40% higher than that on a conventional sapphire substrate. [1] K. Kunihiro, et. al., J. Jour. Appl. Phys., 39, p.2431-2434 (2000)

9:30 AM E10.4
COMPONENTS FOR AlGaN/GaN POWER AMPLIFIER MMICS. Bart Jacobs, Bram van Straaten, Fouad Karouta, Eindhoven Univ. of Techn., Dept. of Electr. Engineering, Opto-Electronic Devices Group, Eindhoven, THE NETHERLANDS; Peter de Hek, Raymond van Dijk, Frank van Vliet, TNO-FEL, MMIC Group, The Hague, THE NETHERLANDS.

In this paper we present our latest results in the development of an AlGaN/GaN based power amplifier. Two research topics will be addressed: 1) Coplanar Waveguide (CPW) transmission lines and discontinuities and 2) multi-finger HEMTs. CPW technology was chosen because it does not rely on via-holes like microstrip. For the development of CPWs AlN was used as a substrate. It has superior insulating properties giving the best results in terms of attenuation/losses in transmission lines. The high current density inside the power amplifier (typically >1A/mm gate width) asks for a large metal cross-sectional area. Measurements on wide (up to 160 um signal line width) CPW transmission lines and discontinuities are presented as well as equivalent circuits describing the RF behavior. It will be shown that for certain geometrical configurations the parallel plate mode is dominant limiting the impedance range that can be realized. In addition to the measurements we will also briefly discuss the modified de-embedding algorithm (LRL) which was used to eliminate the influence of the pad structures. Regarding the multi-finger HEMTs we will present HEMT parameters as a function of total gate width exceeding 1mm. In addition, the processing of these devices will be discussed with special attention on the metal-semiconductor contacts and the sulfite-based electroplating process, which was used to fabricate the airbridges and thick gold layers.

9:45 AM E10.5
MICROWAVE, PULSE AND HIGH-TEMPERATURE CHARACTERISTICS OF LARGE-PERIPHERY AlGaN/GaN MOSHFETS. X. Hu, G. Simin, J. Zhang, A. Tarakji, A. Koudymov, J. Yang, and Asif Khan, Univ. of South Carolina, Dept. of Electrical Engineering, Columbia, SC; M. Shur, R. Gaska, SET Inc., Troy, NY.

Recently published AlGaN/GaN Metal-Oxide Semiconductor heterostructure field-effect transistor (MOSHFET) demonstrates a superior performance due to extremely low gate leakage current. This design allows transistor to operate at high positive gate bias thus increasing the maximum saturation current by approximately a factor of two compared to a regular HFET structure. In this presentation we report on a detailed study of large-periphery MOSHFET devices with multigate geometry. This geometry allows peak current as high as 5 A to be achieved in pulse mode. In DC mode, the overall device heating limits the maximum saturation current. The breakdown voltage up to 600 V can be achieved by using MOSHFET devices with large gate-drain spacing and additional surface passivation. When a pulsed signal is applied to the gate, MOSHFETs demonstrate very short subnanosecond rise/fall times. In this mode the device can be used as a high power switch with more than 7.5 kW/mm2 switching power. Microwave measurements demonstrate nearly linear dependence of the maximum output power on the total gate width of MOSHFET while the cut-off frequency dependence on the total width is quite weak. At high temperatures, up to 300°C the gate leakage current of MOSHFET remains very low, about 6 order of magnitude lower than that of regular HFET. MOSHFET also demonstrates a superior pinch-off behavior at elevated temperatures. These features make a large-periphery MOSHFET an extremely promising device for high-power, high-temperature applications.

10:30 AM E10.6
FACTORS AFFECTING CURRENT COLLAPSE IN AlGaN/GaN HFETS AND MOSHFETS. G. Simin, X. Hu, J. Zhang, A. Tarakji, A. Koudymov, J. Yang and Asif Khan, Univ. of South Carolina, Dept. of Electrical Engineering, Columbia, SC; M. Shur, R. Gaska, SET Inc., Troy, NY.

GaN-based HFETs demonstrate record levels of carrier density in two-dimensional electron gas (2DEG) layers at GaN-AlGaN interface. Extremely high channel currents (above 1A/mm) in conjunction with breakdown voltages above 100 V, suggest the possibility of obtaining record high microwave output powers in GaN-AlGaN FETs. We have recently demonstrated that the maximum saturation current can be further increased, by a factor of two, with no degradation in fT, by using Metal-Oxide-Semiconductor HFET (MOSHFET) device structures. However, both GaN-AlGaN HFETs and MOSHFETs still demonstrate typical RF output powers of about 3-5 W/mm, even under pulsed bias conditions that eliminate heating effects. This is 2-3 times lower power than the one expected from the I-V curves. The phenomenon responsible for this degradation is generally referred as "RF-current collapse" or "current slump" which recently has been a subject of several studies. We report on the detailed comparative study of current collapse in different types of AlGaN/GaN field-effect transistors. We are using pulsed current-voltage characteristics technique to study the current collapse. These pulsed I-V characteristics are further compared to DC and microwave characteristics of the different device types. This comparison was found to reveal the most important features of the current collapse in AlGaN/GaN FETs. More specifically, we conclude that the gate leakage current as the mechanism responsible for current collapse can be ruled out. Also, the high-field domain between gate and drain cannot cause the collapse since the same level of current compression was observed at low grain bias. The quality of buffer layer beneath the 2D electron gas layer is found to be the most important factor affecting the current collapse.

10:45 AM E10.7
DC AND MICROWAVE PERFORMANCE IN AlGaN/GaN METAL-OXIDE-HETEROSTRUCTURE SEMICONDUCTOR FIELD EFFECT TRANSISTORS ON SiC SUBSTRATES UNDER INTENSE HEATING OPERATIONS. A. Tarakji, G. Simin, X. Hu, A. Koudymov, J. Zhang, M. Asif Khan, Univ of South Carolina, Dept of Electrical Engineering, Columbia, SC; R. Gaska, M.S. Shur, Senior Electronic Technology, Inc, Latham, NY.

We report on the high temperature DC and RF performance in AlGaN/GaN metal oxide semiconductor heterostructure field effect transistor (MOS-HFET) over a semi-insulating SiC substrate and present the results of the comparative studies at elevated temperatures of this device DC and RF characteristics and those of a base line AlGaN/GaN heterostructure field effect transistor (HFET) over the same SiC substrate. Device parameters such as gate leakage current, pinch-off voltage, threshold voltage, small-signal trans-conductance, saturation current, unity current gain cut-off frequency (f_T), maximum frequency of oscillation (f_{max}), power added efficiency (PAE), and maximum output power were measured on two MOS-HFETs of different sizes and on two corresponding HFETs of same sizes under temperatures ranging from 300°K to 400°K. Devices with 2 × 25μ and 2 × 100μ gate widths were used in the characterization. We additionally describe for the first time the effects of device heating on the SiO_2 insulating quality in MOS-HFETs, and on the RF current collapse phenomenon in both of MOS-HFETs and HFETs. A flat Thermofoil heater with a temperature controller was used for the on-wafer heating of the devices during measurements. DC characteristics were extracted with an HP multi-meter and a 576 Tektronix curve tracer while the small signal RF measurements were done using an 8510C HP network analyzer. The Maury automated tuning system (ATS) was used in measuring the PAE and the maximum deliverable RF output power. Observed were thermal activations in carriers trappings at elevated temperatures yielding to a

reduction in the RF current collapse mechanism. Also, observed was degradation in the insulating SiO_2 quality at higher temperatures resulting in an increased gate leakage current. The work is supported by the Ballistic Missile Defense Organization (BMDO).

11:00 AM E10.8
TEMPERATURE-DEPENDENT PERFORMANCE OF SELF-ALIGNED GaN/AlGaN HBTs. K.P. Lee, University of Florida, Dept of Materials Science and Engineering, Gainesville, FL; A.P. Zhang, F. Ren, University of Florida, Dept of Chemical Engineering, Gainesville, FL; S.J. Pearton, University of Florida, Dept of Materials Science and Engineering, Gainesville, FL; J. Han, Sandia National Laboratories, Albuquerque, NM; W.S. Hobson, J. Lopata, Bell Labs, Lucent Technologies, Murray Hill, NJ; C.R. Abernathy, University of Florida, Dept of Materials Science and Engineering, Gainesville, FL.

Small and large (100 μm diameter) area GaN/AlGaN HBTs were fabricated using a self-aligned dry etch process [involving regrowth of GaAs (C) on the base region and GaN (Si)/AlGaN (Si) on the emitter in same cases]. The room temperature performance was limited by series resistance and recombination effects. Operation at elevated temperatures (300°C) increased the hole density in the base layer, leading to a substantial decrease in base resistance. However E-B nad B-C junction leakage is an issue at high temperatures. We discuss a systematic study of HBT performance over the temperature range 25-300°C, involving measurement of breakdown voltage, junction leakage and dc current gain.

11:15 AM E10.9
EFFECTS OF A CURRENT SPREADING ON THE PERFORMANCE OF GaN-BASED LIGHT-EMITTING DIODES. Hyunsoo Kim, Dong-Joon Kim, Ji-Myon Lee, Seong-Ju Park, and Hyunsang Hwang, KJIST, Kwangju, KOREA.

Significant progress has been made on our understanding of III-nitride light emitting diodes (LEDs) and laser diodes (LDs). Typically, it is necessary to employ a lateral carrier injection type with respect to these diodes due to the insulating sapphire substrate. However, an employment of the lateral injection type can exhibit a problem of non-uniform current spreading during device operation. It was shown that the non-uniform current spreading could significantly degrade the properties of LED performance due to the current crowding in a localized region of the device. However, the role of current spreading in the GaN-based LEDs has not been clearly understood as yet. In this report, we demonstrate the effects of the current spreading on the electrical, optical and reliability characteristics of the LED using the current-voltage, light output power-injected current density, and the lifetime measurements. In order to study in detail, we propose the device operation model using dominant parameters such as the injected current, effective length for the lateral current path, and resistivities of the transparent electrode and n-type layers. It is well shown that the condition for the uniform current spreading is sensitively dependent upon these parameters. Based on this theoretical model, first, the determination of the critical thickness of the transparent layer is possible by considering the resistivity of the n-type layer. In addition, especially, the geometrical design of the highly efficient and reliable LED was successful. It is noteworthy that the significantly improved performance of LEDs without the transparent electrode could be realized in terms of geometrical modification of the p- and n- electrodes.

11:30 AM E10.10
MODELING OF THE BREAKDOWN VOLTAGE IN GaN RECTIFIERS. Y.S. Lee, M.K. Han and Y.I. Choi, School of Electrical Eng., Seoul National Univ., Shinlim-Dong Kwanak-Ku, Seoul, KOREA.

GaN may be promising wide band-gap semiconductor for high voltage power device due to high electric fields strength and carrier mobility[1]. The breakdown voltage is the most important feature in power semiconductor devices. However, accurate evaluations are rather difficult and analytic model of breakdown voltage in GaN, has been scarcely reported. We have already reported the analytic model of breakdown voltage of SiC rectifiers[2]. The purpose of our work is to report the analytic model of breakdown voltage in GaN reach-through rectifier and to compare the results with SiC reach-through rectifier. In this work, we derive the breakdown voltage of GaN reach-through rectifier from the impact ionization coefficient employing the impact ionization integral. The impact ionization coefficients of GaN, extracted from Monte-Carlo simulation, were reported in wurtzite and zinc-blende in the literatures respectively [3-5] and the hole impact ionization coefficient(α_p) is about two times larger than that of electron over the wide electric field range. $\int_0^W \alpha_p \exp[\int_0^x (\alpha_n - \alpha_p)dx]dx = 1$ where $\alpha_p(x) = M—E(x)—^7$, $\alpha_n = \gamma\alpha_p$ E(x) : Electric field The M of α_p in wurtzite and zinc-blende are 1.767×10^{-42} and 4.749×10^{-41} respectively. We denote α_n as $\gamma\alpha_p$ where γ is constant. By inserting the Poisson's equation into seventh order equation and some integral calculations, the final closed-form solutions of the breakdown voltages as function of doping concentration were successfully derived as $V_B = 1.7118\times10^4 W_B N_D^{1/8} - 1.004\times10^{-9} W_B^2 N_D$ for $N_D \geq 2.316\times10^{14} W_B^{-8/7} = 1.204\times10^6 W_B^{6/7}$ for $N_D \leq 3.472\times10^{13} W_B^{-8/7}$ (wurtzite) $V_B = 1.1344\times10^4 W_B N_D^{1/8} - 1.004\times10^{-9} W_B^2 N_D$ for $N_D \geq 1.447\times10^{14} W_B^{-8/7} = 7.525\times10^5 W_B^{6/7}$ for $N_D \leq 2.169\times10^{13} W_B^{-8/7}$ (zinc-blende) N_D : doping concentrations W_B : Depletion width The wurtzite GaN rectifier exhibited excellent breakdown voltage compared to zinc-blende GaN rectifiers, 6H-SiC, and 4H-SiC rectifiers which we previously reported [2]. The breakdown voltage of the wurtzite GaN rectifier is 55% higher than that of 6H-SiC at the same doping concentrations. The breakdown voltage of zinc-blende GaN rectifier is slightly lower than that of SiC rectifiers in the low doping concentration region. Our analytic model shows that the breakdown voltage of GaN rectifiers is larger than that of SiC rectifiers in high doping concentration regions. Finally, the GaN rectifiers exhibit the better forward characteristics than SiC rectifiers when the breakdown voltage is identical due to the high doping concentration of W_B .

11:45 AM E10.11
X-BAND SILICON CARBIDE IMPATT OSCILLATOR. Konstantin Vassilevski, Ioffe Institute, St. Petersburg, RUSSIAN FEDERATION; Alexandr Zorenko, State Scientific & Research Institute Orion, Kyiv, UKRAINE; Konstantinos Zekentes, Microelectronics Research Group, Foundation for Research & Technology-Hellas, Heraklion, GREECE.

Since the first IMPATT diode was demonstrated, SiC was considered as the most promising material for the fabrication of this device [1]. Nevertheless, SiC IMPATT diodes have not been fabricated yet despite a rapid progress in SiC technology and material characterization. In this paper, we report on the fabrication of the first 4H-SiC IMPATT diodes operating in X band (8.2 - 12.4 GHz). 4H-SiC epitaxial structures have been purchased from Cree, Inc. The low resistivity ohmic contacts to n- and p-doped SiC have been fabricated using Ni_2Si and Ni_2Si/TiC compositions, respectively [2]. The mesa structures have been formed by RIE. The wafer was cut into chips. The diodes were mounted in a micro strip circuit with resonant impedance transformation. To choose the frequency range of measurements and to design the micro strip circuit, results of numerical modeling of 4H-SiC IMPATT diodes have been used. The calculation was performed using the latest experimental data about material parameters submitted in drift-diffusion model of SiC IMPATT diode [3]. The diode was biased to operate at avalanche breakdown. Measurements were performed in pulse mode. Current pulses had the amplitude up to 2 A and the duration up to 100 ns with duty factor of 1000. The 4H-SiC IMPATT oscillator produced the UHF pulsed power of 0.3 W with pulse duration of 40 ns in X-band at pulsed avalanche current of 0.5 A. Detailed description of the 4H-SiC IMPATT diode and UHF measurement scheme will be given in the report. This work was supported by INTAS-CNES 97-1386 project. References 1. A. Tager, V. Vald-Perlov, IMPATT diodes and their application in UHF technique, Moscow, Sov. Radio, 1968 [in Russian]. 2. K. Vassilevski, K. Zekentes, G. Constantinidis, A. Strelchuk, SSE, 44, 1173 (2000). 3. K. Vassilevski, Sov. Phys. Semiconductors, 26, 994, (1992).