SYMPOSIUM T

Wide-Bandgap Electronic Devices

April 24 – 27, 2000

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* Invited paper

SESSION T1: SiC DEVICES
Chairs: Wilfried Pletschen and M. Asif Khan
Monday Afternoon, April 24, 2000
Golden Gate A2 (Marriott)

1:30 PM *T1.1
SiC AND GaN HIGH-VOLTAGE POWER DEVICES. T. Paul Chow, Rensselaer Polytechnic Institute, Troy, NY.

The present status of development of SiC and GaN devices for high-voltage power electronics applications is reviewed. Device structures that are particularly applicable to these two wide bandgap semiconductors are considered and compared to those commonly used in silicon. The simulated and experimental performance of two-terminal rectifiers and three-terminal transistors and thyristors are compared. The effects of material parameters (mobility, ionization coefficients, lifetimes) and defects on device characteristics are pointed out. Similarities and differences between electronic and photonic device development in these semiconductors are discussed.
This work is supported by ONR-MURI (Grant N00014-95-1-1302), DARPA (Contract MDA972-98-C-0001), and NSF Center for Power Electronics Systems (Award Number EEC- EEC-9731677).

2:00 PM *T1.2
ELECTRICAL BEHAVIOR OF X-RAY IMAGED CRYSTAL DEFECTS IN SiC HIGH FIELD DEVICES. Philip G. Neudeck, Maria A. Kuczmarski, NASA Glenn Research Center at Lewis Field, Cleveland, OH; Michael Dudley, William M. Vetter, Haibin B. Su, State University of New York at Stony Brook, NY.

Present understanding of the electrical and physical properties of SiC crystal defects uniquely revealed by X-ray topographic imaging is reviewed. A particular emphasis is placed on ascertaining the electrical behavior of closed core screw dislocations in high-power switching devices, because these difficult to observe defects are present in densities of thousands per square cm in commercial SiC epilayers, and their reduction to much smaller densities so as to eliminate them from highly beneficial SiC-based power switching electronics seems problematic for the forseeable future. In silicon power electronics experience, undesired lateral nonuniformities in electrical material properties across the high field area of a power device, (e.g., nonuniformities caused by crystal dislocation defects and impurity clusters) have historically led to reliability problems in demanding high-power systems, with higher voltage devices being most susceptible to failure. Similar nonuniformities have also been observed in SiC, some of which have been directly linked to closed core screw dislocations. Nevertheless, SiC has strong material property advantages that should make it inherently more durable to localized electrothermal stresses that govern power device safe operating area. Quantitative understanding leading to predictive models for the electrothermal behavior of closed core screw dislocations in various device and circuit topologies are needed if SiC devices containing these defects are going to achieve maximum system performance benefits with high reliability in specific high-power applications. Updated results from on-going experimental and theoretical investigations into the properties of X-ray imaged defects will be presented.

2:30 PM T1.3
DEVELOPMENT OF BROAD TEMPERATURE RANGE Pd/AlN/Si OR SiC MIS HYDROGEN SENSOR. Flaminia Serina, Wayne State Univ, Dept of Chemical Engineering, Detroit, MI; Gregor W. Auner,Wayne State Univ, Dept of Electrical Engineering, Detroit, MI; K.Y. Simon Ng, Wayne State Univ, Dept of Chemical Engineering, Detroit, MI; Ranta Naik, Wayne State Univ, Dept of Physics, Detroit, MI; Changhe Huang, Lajos Rimai, Department of Electrical Engineering, Wayne State University, Detroit, MI.

An AlN (insulator) MIS Hydrogen Sensor was created using Plasma Source Molecular Beam Epitaxy (PSMBE) deposition on 6H-SiC and Si(111) substrates. The employment of AlN, instead of conventionally used SiO_2 or TiO_2, allows the device to operate at high temperatures as well as room temperature. A Pd layer was deposited on top of the AlN film via Magnetron Sputtering technique utilizing a hard mask. Pd was chosen since H2 readily diffuses within its bulk, thus Pd acts not only as the metal electrode of the MIS structure but also as the catalyst for H2 dissociation. To optimize the design structure several sensors with different AlN and Pd thickness have been developed. RHEED and XRD showed that the AlN film is epitaxial to the Si (111) as well as to the 6H-SiC substrates. The sensors were characterized using Capacitance vs. Voltage (C-V) measurements and I-V measurements, at different frequencies ranging from 1kHz to 1 MHz. When Hydrogen was introduced in the testing chamber a shift in the C-V curve occurred. Similar results were obtained as I-V measurements were performed. The temperature and H2 partial pressure responses of the sensor were analyzed and a satisfactory response occurred even at room temperature.

3:15 PM *T1.4
WIDE BANDGAP SEMICONDUCTOR APPLICATIONS - AN AIR FORCE PERSPECTIVE. Laura Rea, US Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, OH.

The Department of Defense (DoD) is investing in the development of wide bandgap semiconductors, including silicon carbide (SiC) and gallium nitride (GaN), for a wide range of applications. Over the past several years, this technology has demonstrated excellent device performance results for power devices, high temperature electronic devices and rf devices. The materials growth and processing technology for wide bandgap semiconductors is now at a level of sufficient maturity to support substantial device development efforts. Considerable materials and device research is still required, however, for wide bandgap semiconductors to reach their full potential. A perspective on selected Air Force device performance requirements will be presented. The status of wide bandgap semiconductor materials development efforts, specifically material limits to advances in device performance, will also be discussed.

3:45 PM *T1.5
COMPREHENSIVE STUDY OF THE ELECTROTHERMAL OPERATION OF SiC POWER DEVICES USING A FULLY COUPLED PHYSICAL TRANSPORT MODEL. Gerhard Wachutka, Martin Lades, Winfried Kaindl, Institute for Physics of Electrotechnology, Munich University of Technology, Munich, GERMANY.

Among all wide bandgap electronic devices, silicon carbide (SiC) power devices receive particular attention for challenging industrial applications in the fields of high-voltage engineering and power transmission. In the past decade, enormous progress has been made in SiC process and device technology which is documented by various well-performing prototypes of high power devices exploiting the attractive features of SiC as electronic material: Robust bipolar operation under high temperature conditions due to the high intrinsic temperature and the excellent thermal conductivity, very high blocking capability of reverse-biased pn- and Schottky-junctions due to the wide energy gap, and significant reduction of switching losses as a result of the much smaller amount of stored charge in the on-state compared to conventional silicon devices. The development of SiC power devices is facilitated and accelerated by the numerical analysis of their operation on the basis of accurate physical device models. This allows visualizing the internal life of a device and thereby, on the one hand, to identify deficiencies and failure mechanisms which are not yet understood satisfactorily so far, and, on the other hand, to optimize the device performance in the various regimes of the operating area by an improved design. To this end, we formulated a comprehensive self-consistently coupled electrothermal transport model which accurately decribes, on the continuous-field level, various physical effects particularly relevant to SiC devices. They include, among others, several field-dependent generation-recombination mechanisms specific of wide-gap materials and their impact on the blocking capability, the consequences of anisotropic material properties such as the carrier mobilities and electric permittivity, the effect of incomplete dopant ionization, and the action of trap dynamics and impurity kinetics on fast switching transients (e.g., dynamic punch-through). We demonstrate the implications of all these effects by selected examples of real devices which were investigated by numerical simulation as well as by experimental characterization, thus allowing us immediate comparison and calibration of the model parameters.

4:15 PM T1.6
ELECTRICAL AND STRUCTURAL PROPERTIES OF METAL/AlN/n-TYPE 6H-SiC(0001) HETEROSTRUCTURES. M.O. Aboelfotoh, North Carolina State University, Raleigh, NC.

Aluminum nitride (AlN) is a wide bandgap semiconductor (6.2 eV) which is nearly perfectly lattice and thermally matched to 6H silicon carbide (SiC) allowing the growth of high-quality epitaxial layers on 6H-SiC. In addition, AlN has a low dielectric constant (ϵ_0=8.5) and a high breakdown field ($\sim 1.5\times 10^7$ V$\times$cm^{-1}). These properties make AlN an attractive candidate for the formation of nearly ideal heterointerface with 6H-SiC, which can be exploited in metal/AlN/6H-SiC (MIS) device structures. In this paper, we report results from a study of the electrical and structural properties of such MIS heterostructures. The MIS heterostructures have been prepared by epitaxially growing wurtzite AlN layers on Si-terminated (0001) surfaces of n-type 6H-SiC substrates using gas-source molecular beam epitaxy. High-resolution transmission electron microscopy results show that the interface between the AlN layer and the 6H-SiC (0001) substrate is microstructurally abrupt. The capacitance-voltage characteristics obtained for these MIS heterostructures are found to depend strongly on temperature in the range of 200 to 500 K, and to exhibit hysteresis effects consistent with the presence of slow interface traps. The amount of hysteresis is found to increase with decreasing temperature. This effect can be explained in terms of the shift of the Fermi level closer to the semiconductor conduction band with decreasing temperature, causing the emission rate of the trapped charge to be less dependent on temperature [1]. The interface is found to have a density of trapped negative charge of 3×10^{11} cm^{-2} at room temperature without any postgrowth treatment. The results suggest that these charges reside largely in such slow interface traps which are likely associated with bonding defects introduced at the interface during the growth of wurtzite AlN. However, this value of negative charge trap density is comparable to those reported for deposited oxides on n-type 6H-SiC (0001), and indicates that the interface between AlN and Si- terminated 6H-SiC is of a high quality suitable for device application.

[1] L.S. Wei and J.G. Simmons, Solid-State Electron. 17, 1021 (1974); J.G. Simmons and L.S. Wei, Solid-State Electron. 16, 53 (1973).

4:30 PM T1.7

IMPLANTED BIPOLAR TECHNOLOGY IN 4H-SiC. Nick Wright, Mark Johnson, Anthony O'Neill, Alton Horsfall, Sylvie Ortolland, Kazu Adachi, The University of Newcastle, Newcastle, UNITED KINGDOM; Andy Knights, The University of Surrey, Guildford UNITED KINGDOM.

A simple ion-implanted bipolar transistor technology in 4H-SiC is presented. Suitable for both high-voltage vertical devices and lateral high-temperature transistors (for circuit applications), the technology is based on an implanted boron p-well with nitrogen and boron (or aluminium) implanted n+ and p+ regions respectively. The effects of post-implant anneal conditions on the electrical characteristics of the junctions will be presented. In addition, techniques for post-anneal surface recovery using RIE etch coupled to oxidation/strip processing will be presented. Using such techniques, low-leakage transistors with breakdown voltages well in excess of 1000V and have been produced and detailed electrical characterization up to 700K performed. The effects of base doping and carrier lifetime on device performance have been studied using TCAD techniques and correlated against measured device performance. It is shown that understanding the strong variation of carrier concentration with temperature (due to deep activation levels) and applied field (so-called field ionization) is critical in device design optimisation.

4:45 PM T1.8

ISOTHERMAL I-V CHARACTERISTIC OF 4H-SiC PN DIODES WITH LOW SERIES DIFFERENTIAL RESISTIVITY AT AVALANCHE BREAKDOWN. K. Vassilevski, Ioffe Institute, St. Petersburg, RUSSIA; K. Zekentes, Foundation for Research & Technology-Hellas, Heraklion, Crete, GREECE; A. Zorenko, State Scientific & Research Institute Orion, Kyiv, UKRAINE; L. Romanov, Closed Joint Stock Company Svetlana-Electronpribor, St. Petersburg, RUSSIA.

4H-SiC is considered as a promising material for fabrication of high power microwave diodes (e.g. p-i-n and IMPATT diodes). This kind of diodes does not need large area mesa structures and may utilize commercial epitaxial wafers having relatively high defect and micro-pipe densities if an appropriate device processing is employed. It has to allow the fabrication of pn diodes having low differential resistance, low capacitance and capable to dissipate high specific electric power. We report on fabrication and electrical character- ization of 4H-SiC pn diodes with extremely low differential resistance. Mesa structures were formed on commercial 4H-SiC pn epitaxial wafer. Wafer was cut into chips, which were mounted in standard microwave diodes packages. Diodes had zero bias capacitance from 2 to 5 pF depending on mesa structure diameter, series differential resistance ~5 Ohm measured at forward bias and avalanche breakdown voltage of 270 V. They were capable to dissipate power density of 150 kW/sq.cm at CW avalanche current 16 mA, and 4.2 MW/sq.cm at pulse avalanche current 1.1 A. The isothermal I-V characteristics of the diodes were measured at the front edge of the pulse. Diode structure parameters obtained from C-V, I-V and SIMS measurements, as well as published data for avalanche ionization rates in 4H-SiC were substituted in a drift-diffusion model to calculate the theoretical isothermal I-V characteristics of investigated diode structure. This numerical model was used to fit the experimental results and the value of electrons saturated drift velocity (ve) in direction along the C axis was the fit parameter. By this way, the value of ve=0.6e7 cm/s was determined. This work was supported by INTAS 97-1386 and NATO SfP71879 projects.

SESSION T2: III-NITRIDE DEVICES–ELECTRONIC

Chairs: Philip G. Neudeck and Mary H. Crawford
Tuesday Morning, April 25, 2000
Golden Gate A2 (Marriott)

8:30 AM *T2.1

GaN-BASED HETEROSTRUCTURES. WHERE DO 2D AND HOLES ELECTRONS COME FROM AND HOW FAST THEY MOVE? Michael S. Shur, ECSE and CIEEM, Rensselaer Polytechnic Institute, Troy, NY.

GaN combines high electron mobility and high saturation and peak velocities with a very high two-dimensional (2D) electron sheet density at the AlGaN/GaN heterointerface (up to 20 times higher than for the GaAs/ AlGaAs materials system). Just like in AlGaAs/GaAs heterostructures, doping the wide band gap AlGaN (or AlGaInN) layer can induce two-dimensional electrons or holes at the GaN/AlGaN heterointerface. However, GaN and AlGaN have strong pyroelectric and piezoelectric properties and the difference in spontaneous polarizations of AlGaN and GaN and strain can induce much larger concentrations of two-dimensional electrons or holes at the heterointerface (depending on the top surface polarity of the heterostructure). Even a light n-type doping of the GaN channel at the heterointerface changes the band diagram and might lead to electron real space transfer. Our calculations show that electron runaway reduces the 2D electron peak velocity compared to the bulk GaN. (In very short devices, this effect might be compensated by velocity overshoot.) Holes accumulated at the AlGaN/GaN heterointerface have a very small mobility, and, at relatively sheet hole concentrations, they are expected to retain their bulk properties. I will discuss the consequences of these effects for the design of high-power and high frequency GaN-based field effect transistors and heterostructure bipolar transistors.

9:00 AM *T2.2

LOW INTERFACIAL DENSITY OF STATES IN $Ga_2O_3(Gd_2O_3)$/ GaN AND SiO_2/GaN MOS DIODES. M. Hong, K.A. Anselm, J. Kwo, H.M. Ng, J.N. Baillargeon, A.R. Kortan, J.P. Mannaerts, A.Y. Cho, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; J.I. Chyi, EE Dept., Natl. Central Univ., TAIWAN; T.S. Lay, Inst. Electro-Optical Eng., Natl Sun Yat-Sen Univ., TAIWAN.

GaN based field-effect transistors (FETs) utilizing Schottky barrier gates have potential applications in the area of high power switching and device operation at high temperatures. However, it has been difficult to achieve stable Schottky contacts at high temperatures. Moreover, device performance degrades due to the presence of high parasitic resistances. The conventional approach, using a n^+-cap layer to reduce parasitic resistance in GaAs technology, is not applicable to these FETs as it is difficult to perform a gate recess. The problems may be overcome by using GaN based metal-oxide-semiconductor FETs (MOSFETs). The MOSFETs would provide for low leakage currents and reduce power consumption. For achieving the merits of a MOSFET, a low density of states (D_{it}) at the oxide/GaN interfaces is a requirement. Recently, we have achieved a low (D_{it}) in Ga_2O_3 (Gd_2O_3)/GaN and SiO_2/GaN MOS diodes. GaN samples on sapphire substrates were prepared using MBE or MOVPE. They were heated up to 650°C in UHV for cleaning the surface contaminants caused by air exposure. $Ga_2O_3(Gd_2O_3)$and SiO_2 8-20nm thick were evaporated by electron beam from a single crystal $Ga_5Gd_3O_{12}$ garnet or quartz. Capacitance-voltage (C-V) measurements on both types of MOS diodes indicate a clear transition between accumulation and depletion and no shift in the flat-band voltage with frequency. Deep depletion can be reached at all frequencies and sweep rates tested, indicating that the generation rate of minority carriers near the surface is not sufficient to form an inversion layer. Judging from the C-V curves, a low D_{it} of less than $10^{11}cm^{-2}eV^{-1}$ was achieved. Leakage current and oxide breakdown will be discussed. The $Ga_2O_3(Gd_2O_3)$/GaN interface remains intact with the samples subject to rapid thermal annealing up to 950°C, as studied from x-ray reflectivity measurements. The interfacial structures were studied by RHEED, x-ray reflectivity, and cross-section TEM.

9:30 AM T2.3

AlGaN/GaN METAL OXIDE SEMICONDUCTOR HETERO-STRUCTURE FIELD EFFECT TRANSISTOR. M. Asif Khan, X. Hu, G. Simin, A. Lunev and J.W. Yang, Dept of Electrical and Computer Engineering, University of South Carolina, Columbia, SC; R. Gaska, Sensor Electronics Technology, Inc., Latham. NY; M.S. Shur, Nezih Pala and S. Rumyantsev, Center for Integrated Electronics and Electronic Manufacturing and Dept of Electrical, Computer and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY.

We report on the AlGaN/GaN Metal Oxide Semiconductor Hetero-structure Field Effect Transistor (MOS-HFET) and present the results of the comparative studies of this device and a base line AlGaN/GaN Heterostructure Field Effect Transistor (HFET). The devices were grown on sapphire and 4H-SiC substrates. For both sets of devices, the maximum current in MOS-HFETs was close to that for HFETs. However, the MOS-HFETs has a much larger dynamic range, a six orders of magnitude smaller leakage current, and comparable or smaller 1/f noise. Hence, the contribution of the SiO_2/AlGaN interface to low-frequency noise is negligible, which confirms a high quality of this interface. The cutoff frequency of MOS-HFETs grown on 4H-SiC was higher than that for the HFETs (with the cutoff frequency-gate length product as high as 16 GHz micron). This value of the cutoff frequency corresponds to the effective electron velocity in the channel close to 100,000 m/s. High temperature characteristics of MOS-HFET are also equal or better than those for the HFET. These results clearly establish the potential of using the AlGaN/GaN MOS-HFET devices for high voltage high temperature applications.

10:15 AM *T2.4

AlGaN BASED T/R MODULES. John C. Zolper, Office of Naval Research, Arlington, VA.

AlGaN High Electron Mobility Transistors (HEMTs) have made great progress for solid state power amplifiers with the demonstration of an X-band power density over 9 W/mm. This high power density is the result of the high current and voltage capability of this material system. Recently, it has also been shown that these devices can be optimized for very low microwave noise figures (NF = 0.8 dB at 10 GHz) while maintaining a large breakdown voltage (> 50V) and hence a large dynamic range. These results imply that AlGaN HEMTs can from a full transmit and receive module that is more robust than conventional technology. Issues relating to realizing a fully AlGaN-based T/R module MMIC will be explored at the conference.

10:45 AM T2.5

DC AND RF CHARACTERISTICS OF HIGH POWER AlGaN/GaN FIELD EFFECT TRANSISTORS GROWN BY RF PLASMA ASSISTED MBE. R. Vetury, I.P. Smorchkova, S. Keller, U.K. Mishra, Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA; C.R. Elsass, B. Heying, J.S. Speck, Materials Department, University of California, Santa Barbara, CA.

We report DC and RF characteristics (small and large signal) of undoped AlGaN/GaN HFETs grown by RF plasma assisted MBE on sapphire substrate. The dependence of the spontaneous and piezoelectric polarization contribution to the 2DEG charge density was characterized as a function of the Al mole fraction (8%-27%) and the thickness of AlGaN layers (30-500 Angstrom). The DC and RF performance of such undoped HFETs was characterized as a function of the Al mole fraction. For devices with Al mole fraction of 0.25 with gate length of 0.7 micron, maximum drain current exceeded 1 A/mm and measured unity current gain cutoff frequency was 22.5 GHz. Microwave power density measured using an ATN load pull system was 3.55 W/mm at 6 GHz with corresponding maximum PAE of 33.5% . These results exceed the best reported power performance of MBE grown GaN HFETs and rival the best reported power performance of MOCVD grown GaN based HFETs on sapphire thus demonstrating the excellent capability of MBE grown GaN for microwave power applications.

11:00 AM T2.6

POTENTIAL OF GaN GUNN DEVICES FOR HIGH POWER GENERATION ABOVE 200 GHZ. Ridha Kamoua, Yiming Zhu, SUNY at Stony Brook, Dept of Electrical and Computer Engineering, Stony Brook, NY; Yunji Corcoran, RSM Sensitron, Deer Park, NY.

This paper investigates the potential of Gallium Nitride (GaN) Gunn diodes for generating high power radiation at millimeter and submillimeter wave frequencies. Simulations were carried out using a computer model based on the ensemble Monte Carlo method. This model accounts for thermal effects, series resistance, and device circuit interaction through the harmonic balance technique. The accuracy of the model has been verified in the case of InP Gunn devices at frequencies above 100 GHz. Initially uniform and linearly graded doping profiles in the active region were considered. It is found that, similar to devices based on InP, the graded profile resulted in a much improved performance in terms of power, efficiency, and operating temperature. In particular, a GaN Gunn structure consisting of a 1 μm thick active region with a graded doping profile increasing from 5×10^{15} cm^{-3} at the cathode terminal to 4×10^{16} cm^{-3} at the anode terminal yielded promising results. The DC bias voltage was estimated from the calculated velocity-electric field data to be about 25 V. With this bias, it was found that oscillations in the fundamental mode could be obtained over the frequency range from 200 GHz to 300 GHz subject to a load resistance of at least 1 Ohm and a maximum operating temperature of 800 K. The maximum output power was 100 mW at 260 GHz with a corresponding conversion efficiency close to 1 %. This estimated power level is about an order of magnitude higher than what can be achieved from second harmonic InP Gunn oscillators at the same frequency.

11:15 AM T2.7

GaN POWER RECTIFIERS. X.A. Cao, Dept MSE, Univ of Florida, Gainesville, FL; G. Dang, A.P. Zhang, F. Ren, Dept Chemical Engineering, Univ of Florida, Gainesville, FL; S.J. Pearton, Dept MSE, Univ of Florida, Gaiensville, FL; J. Han, Sandia National Laboratories, Albuquerque, NM; J.-I. Chyi, C.-M. Lee, C.-C. Chuo, Dept Chemical Engineering, National Central Univ, Chung-Li, TAIWAN.

GaN Schottky diode and p-i-n rectifiers were fabricated on a range of different MOCVD-grown material. Reverse breakdown voltages were typically in the range 350-550 V for standard MOCVD layers, but can reach values above 2 kV on insultating material. Figures-of-merit $(V_RB)^2/R_ON$ are in the 5-50 MW$\cdot$ cm_{-2} range, emphasising the potential of these devices for power switching applications. Unpassivated devices typically display a negative temperature coefficient for the reverse breakown voltage. Current densities are typically higher in the p-i-n structures, at the expense of higher turn-on voltages, but the on-voltages still need improvement in the Schottky rectifiers. A comparison will be given with state-of-the-art Si and SiC power rectifiers.

11:30 AM T2.8

HIGH PERFORMANCE GaN/AlGaN HIGH ELECTRON MOBILITY TRANSISTORS GROWN DIRECTLY ON SiC BY MOLECULAR BEAM EPITAXY. Miroslav Micovic, Nguyen Nguyen, Danny Wong, Paul Hashimoto, Loren McCray, David Grider, Chanh Nguyen, HRL Laboratories, Malibu, CA.

We report power performance of GaN/AlGaN High Electron Mobility Transistors (HEMT's) fabricated from layers grown by molecular beam epitaxy (MBE) on two-inch diameter SiC substrates. The output power density of 6.5 W/mm measured for these devices at 8 GHz is to the best of our knowledge the highest ever reported for a GaN HEMT grown by MBE. The epitaxial layers for HEMT fabrication were deposited directly onto Si-face of semi insulating (0 0 0 1) oriented 4H SiC using atomic nitrogen plasma source. The structure used for HEMT fabrication was grown in following order: 10 nm thick AlN nucleation layer, 2 μm thick GaN layer and 24 nm thick AlGaN Schottky barrier layer. The composition of AlGaN Schottky layer was empirically adjusted to induce piezoelectric sheet charge of 1.2×10^{13} cm^{-2} at AlGaN/GaN interface. For the described HEMT structure we consistently obtain room temperature 2DEG Hall effect mobility of over 1200 cm^2/Vs. Transistors with 0.25 μm x 200 μm gates fabricated from this material by our established process have unity current gain cutoff frequency of 50 GHz and maximum frequency of oscillations of over 100 GHz. The peak power density of 6.5 W/mm that was measured for these devices at 8 GHz is to the best of our knowledge the highest ever reported for a MBE grown GaN HEMT. The variation in peak power density that was measured across the 2 inch wafer for identical biasing conditions was less than 5%. Our results clearly demonstrate that MBE may be a technique of choice for growth of GaN HEMT layers, because it provides excellent material quality and uniformity required for fabrication of large power circuits, and good run to run reproducibility required for large scale production and yield.

11:45 AM T2.9

FABRICATION OF ENHANCEMENT MODE GaN-BASED METALINSULATOR SEMICONDUCTOR FIELD EFFECT TRANSISTOR. P. Chen, R. Zhang, Y.G. Zhou, S.Y. Xie, Z.Y. Luo, Z.Z. Chen, W.P. Li, B. Shen, Y. Shi, S.L. Gu, Y.D. Zheng, Department of Physics, Nanjing University, Nanjing, CHINA; Z.C. Huang, Raytheon ITSS, MD.

Recently, a number of GaN-based field-effect transistors (FETs) have been reported. For many applications, metal-insulator-semiconductor technology is desirable since it would provide high DC input impedance, large gate voltage swings, normally-off operation with high source-drain blocking voltage, and high temperature operation as a result of reduced gate leakage comparing to that of a conventional metal semiconductor FET (MESFET). Using plasma-enhanced chemical vapor deposition (PECVD) deposited SiO_2 on a GaN layer, we have obtained a good MIS capacitor with low interface state density and excellent high-frequency capacitance-voltage (C-V) characteristic. However, for a semiconductor with a wide energy gap, the generation of minority carries in the GaN MIS capacitor would be extremely slow. Therefore, it would be very difficult to obtain an inverted channel in a GaN MISFET with a conventional device structure. In this work, we demonstrate an enhancement mode GaN-based MISFET on a GaN/ $Al_{0.4}Ga_{0.6}N$/GaN double hetero-junction with PECVD-grown SiO_2 as a gate insulator. The gate leakage current is lower than 10^{-6}A at a bias of -10 V and the gate breakdown voltage is higher than 20V. The enhancement mode DC characteristics have been achieved for the first time in the device with gate lengths of 6μm and 10μm and a gate width of 100μm. The device with a gate length of 6μm exhibited a DC transconductance of 0.6 mS/mm and a maximum drain-source current of 0.5 mA. This result is attributed to the presence of a piezoelectric field in the hetero-junction and the strongly asymmetric band bending and carriers distribution induced by the piezoelectric field. High-frequency capacitance-voltage measurements confirmed the presence of a p-channel in the device structure.

SESSION T3: III-NITRIDE DEVICES–ELECTRONIC AND PHOTONIC

Chairs: Michael S. Shur and John C. Zolper
Tuesday Afternoon, April 25, 2000
Golden Gate A2 (Marriott)

1:30 PM *T3.1
MBE GROWTH OF GaN-BASED HETEROJUNCTION BIPOLAR TRANSISTORS AND BIPOLAR JUNCTION TRANSISTORS. J.M. Van Hove, J.J. Klaassen, A.M. Wowchak, C.J. Polley, D.J. King, P.P. Chow, SVT Associates, Eden Prairie, MN; X.A. Cao, C.R. Abernathy, S.J. Pearton, Department of Materials Science and Engineering, University of Florida, Gainesville, FL; F. Ren, G. Dang, A.P. Zhang, Department of Chemical Engineering, University of Florida, Gainesville, FL.

GaN/AlGaN bipolar transistors are an attractive option for various satellite, radar and communications applications in the 1-5 GHz frequency range, at temperatures >400°C and powers >100 Watts. In this paper we report on the growth, fabrication, and testing of both bipolar (BJT) and heterojunction bipolar transistors (HBT) in the nitride material system. The active regions of these transistors were grown by Molecular Beam Epitaxy using a rf plasma source to provide atomic and excited molecular nitrogen. Solid source Ga, Al, Mg and Si sources were used. Various in-situ characterization techniques such as cathodoluminescence, RHEED, and optical pyrometry (to obtain both the growth rate and substrate temperature) were used to optimize the device growth. A low damage Cl_2/Ar dry etch process was used to fabricate devices with emitters that ranged in diameter between 50 and 100 μm. Both HBTs and BJTs were characterized at room temperature and 250-300°C. At 25°C, we obtained maximum current densities of 2.55 kA·cm^{-2} at V_{BC}=8V, corresponding to power densities of 20.4 kW·cm^{-2} for the HBT structure. At 250°C, the maximum current density was 2.55 kA·cm^{-2} at ~4 V, corresponding to a power density of 10.2 kW·cm^{-2}. Room temperature common emitter gain for these devices was in the range of 15-20. The breakdown voltage in both types of devices decreased at higher temperatures, with less degradation in the BJT structure. In the common-base mode of operation, I_C was approximately equal to I_E, indicating high emitter injection efficiency. This mode of operation is attractive because of the possibility of power gain through impedance transformation.

2:00 PM T3.2
GaN P-N-P BIPOLAR JUNCTION TRANSISTOR OPERATED TO 250°C. A.P. Zhang, G. Dang, F. Ren, Univ of Florida, Dept of Chemical Engineering, Gainesville, FL; J. Han, C. Monier, A.G. Baca, Sandia National Laboratories, Albuquerque, NM; X.A. Cao, H. Cho, C.R. Abernathy, S.J. Pearton, Univ of Florida, Dept of Materials Science and Engineering, Gainesville, FL.

There is strong interest in the development of GaN bipolar transistors for the high temperature (>400 °C), high power (>100 W) applications involving space and terrestrial communications link and phased array radar. Since the npn bipolar device suffers from high base resistance due to the relatively low hole concentrations obtained in p-GaN, an attractive alternative is the pnp configuration because it is easier to achieve heavy base doping in n-GaN and the higher carrier mobility in n-type materials would reduce base resistance. In this talk, we report the first demonstration of GaN p-n-p bipolar junction transistor (BJT). The structure was grown by MOCVD on c-plane sapphire substrates and mesas formed by low damage Inductively Coupled etching with Cl_2/Ar chemistry. The dc characteristics were measured up to V_{BC} of 65 V in the common base mode and at temperature up to 250 °C. Under all conditions, $I_C \sim I_E$ indicated the high emitter injection efficiency. The offset voltage was $\leq$2 V and the devices were operated up to power densities of 13.9 kW.cm^{-2}.

2:15 PM T3.3
CURRENT GaIN SIMULATION OF AlGaN/GaN Npn HETEROJUNCTION BIPOLAR TRANSISTORS. C. Monier, S.J. Pearton, Dept of Materials Science and Engineering, University of Florida, Gainesville, FL; A.G. Baca, P.C. Chang, L. Zhang, J. Han, R.J. Shul, Sandia National Laboratories, Albuquerque, NM; F. Ren, J.R. LaRoche, Dept of Chemical Engineering, University of Florida, Gainesville, FL.

The wide band-gap, nitride-based semiconductors have great potential for the realization of high temperature and high power electronics due to high-saturated electron velocities and high breakdown voltages. Recently two reports have appeared on operation of Npn AlGaN/GaN heterojunction bipolar transistors (HBTs). Current gains β of 3 on large area devices were produced at room temperature. High recombination rates in the base and difficulties to get sufficiently high p-type doping levels are thought to be responsible of this low β value. The purpose of this paper is to theoretically investigate the epitaxial and geometrical design of the device in order to achieve higher current gain values in DC mode operation. We have performed at room temperature simulations of the electrical performance of the Npn GaN-based HBT using a two dimensional self-consistent program based on the drift-diffusion model. Physical models incorporated in the simulation include carrier statistics, generation-recombination mechanisms and specific contact resistance for both n and p-type materials. The experimental Gummel plot from the initial large area HBT structure agrees well with simulation by using concentration-dependent minority carrier mobility μ and lifetime τn values resulting from careful analysis of data available in the literature. Different approaches have been considered to improve the Npn HBT performance. Since recombination mechanisms are dominant in the base region for GaN materials characterized by high density of threading dislocations, the current gain is expressed as the ratio of τn to the minority carrier transit time τb across the base. Moderate improvement of the DC current gain (by a factor of ~2) is observed by reasonably reducing the base thickness in accordance with inherent processing limitations. Base transport enhancement is also predicted by the introduction of a quasi-electric field in the base. This field is practically established by the grading of the aluminum concentration in the base. Simulations have been performed for various graded conduction band profiles with electric field values up to 40kV/cm. As a result, compositionally graded structures exhibit current gain significantly higher (β > 20) than those from non-graded structures. The effects of reduced base doping (to improve mobility and lifetime) and smaller active areas (to make the transistor well suited for AC testing) have been also investigated.

2:30 PM T3.4
ACCUMULATION HOLE LAYER IN INVERTED p-GaN/AlGaN HETEROSTRUCTURES. M.S. Shur, A.D. Bykhovski and R. Gaska, Center for Integrated Electronics and Electronic Manufacturing and Department of Electrical, Computer and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY; J.W. Yang, G. Simin and M. Asif Khan, Department of Electrical and Computer Engineering, University of South Carolina, Columbia, SC.

We present experimental data for an inverted p-GaN/AlGaN heterostructure with accumulation hole layer and compare these data with the results of the band structure calculations. In the temperature range from 300 K to 450 K, the hole mobility is a weak function of temperature and varies from 5 to 3 cm^2/V-s. The calculations account for spontaneous and piezoelectric polarizations, as well as for strain relaxation. The calculation results show that the polarization charges can induce up to 5x10^{13} cm^{-2} holes at the AlGaN/GaN hetero-interface. We also discuss the relationship between the thickness of the hole accumulation layer and the hole mean free path. This analysis shows that the 2D hole gas can only exist at high sheet hole concentrations (exceeding 10^{13} cm^{-2}). For smaller densities, the holes in the accumulation layer should have the same transport properties as in the bulk. The results suggest that a polarization-induced 2D-hole gas can be used for the reduction of the base spreading resistance and contact resistance in AlGaN/GaN-based bipolar transistors and heterostructure bipolar transistors.

3:15 PM *T3.5
(AlGaIn)N HETEROSTRUCTURES: FROM MATERIALS RESEARCH TO LIGHT EMITTING DEVICES. J. Wagner, A. Ramakrishnan, H. Obloh, M. Kunzer, P. Schlotter, W. Pletschen, R. Kiefer, U. Kaufmann, M. Maier and K. Koehler, Fraunhofer-Institut für Angewandte Festkoerperphysik, Freiburg, GERMANY.

Group III-nitride based heterostructures are of rapidly growing importance for the fabrication of short wavelength light emitting devices. The precise knowledge of basic material parameters greatly facilitates the design and realization of high performance devices. First, basic material issues will be addressed such as the composition dependence of the band gap energies of AlGaN and InGaN as well as the band offset between GaN and InGaN. Next, the effect of built-in piezoelectric fields on the optical properties of InGaN/GaN quantum wells (QWs) will be reviewed, including implications for an optimized InGaN QW width for LED applications. Finally, results on GaN/InGaN/AlGaN QW LEDs covering the 400 to 430 nm wavelength range will be presented.

3:45 PM *T3.6
DESIGN AND PERFORMANCE OF NITRIDE-BASED ULTRAVIOLET LEDS. Mary H. Crawford, Jung Han, Sandia National Laboratories, Albuquerque, NM.

While the majority of nitride light emitting device development has focused on InGaN multiquantum well structures for visible wave-

lengths, quantum well active regions based on GaN, AlGaN and/or AlGaInN materials are also quite promising, and are well suited for the development of ultraviolet (UV) emitters. UV LEDs are of particular interest as an excitation source for white lighting applications, where the UV wavelengths offer the potential for higher efficiencies than has already been achieved from white LEDs based on InGaN blue LED technology. The UV heterostructures present a number of distinct challenges, including doping and strain effects in higher Al composition AlGaN layers, absorption effects from GaN buffer and contact layers, and achieving sufficient carrier confinement and optical efficiency. In this talk, we will overview several of the critical materials growth, design and performance issues for nitride-based UV (< 390 nm) LEDs. We will compare the performance of a number of distinct UV LED devices, including structures with GaN/AlGaN quantum well active regions, structures with InGaN active regions in the low ($x < 0.07$) indium composition regime, and structures incorporating AlGaInN quaternary alloys as either the well or barrier material. The critical issue of whether the UV heterostructures can achieve high optical efficiency will be examined through time-resolved and temperature-dependent photoluminescence studies of the various UV active regions.
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the U.S. Dept. of Energy under contract DE-AC04-94AL85000.

4:15 PM *T3.7
PRESENT STATUS OF III-NITRIDE UV PHOTODETECTORS.
Eva Monroy, Fernando Calle, Elias Munoz, Dept Ingeniería Electrónica, Univ. Politécnica de Madrid, Madrid, SPAIN; Franck Omnès, Bernard Beaumont, Pierre Gibart, CRHEA-CNRS, Valbonne, FRANCE.

UV photodetection has drawn a great deal of attention in the recent years, due to the rise of new requirements. Both civil and military industries demand better UV instrumentation, for applications such as engine control, solar UV monitoring, source calibration, UV astronomy, flame sensors, detection of missile plumes, and secure space-to-space communications. Wide-bandgap compounds are the best choice for UV detectors, since they combine the advantages of compact, low-bias, semiconductor devices, with their intrinsic visible-blindness and higher stability. III-Nitrides (AlN, GaN, and InN) present some advantages over other wide-bandgap semiconductors, such as high absorption coefficients and sharper cutoffs, due to their direct bandgap, the possibility of selecting the cutoff wavelength by changing the mole fraction of their ternary alloys, and their capability for heterojunction devices. In this work, we summarize our recent achievements in AlGaN-based UV photodetectors, including photoconductors, Schottky barrier detectors, metal-semiconductor-metal photodiodes, and p-n junction photodiodes. The main features of the different devices (spectral responsivity, bandwidth, noise), and the models proposed to explain their performance. The effect of material quality will be discussed, including a comparison between standard devices and photodetectors grown on epitaxial lateral overgrown GaN.

4:45 PM T3.8
A COMPARATIVE STUDY OF AlGaN- AND GaN-BASED LASING STRUCTURES FOR NEAR- AND DEEP-UV APPLICATIONS.
Sergiy Bidnyk, Jack Biu Lam, Brian Dean Little, Yong-Hwan Kwon and Jin-Joo Song, Oklahoma State Univ, Center for Laser and Photonics Research and Dept of Physics, Stillwater, OK.

We report a comprehensive study on the optical properties of GaN-and AlGaN-based lasing structures at high-levels of optical excitation (carrier densities of 10^{17}-10^{20} cm^{-3}) and identify critical issues necessary for the development of near- and deep-UV light emitting devices. We successfully achieved room temperature stimulated emission (SE) with emission wavelengths ranging from 330 nm to 375 nm in a variety of samples studied. Through an analysis of the temperature-dependent lasing characteristics, combined with absorption and time-resolved photoluminescence measurements, we estimated the Mott density in GaN to be 1.1×10^{18} cm^{-3}. We found that in AlGaN epilayers, the onset of SE occurs at carrier densities of $\sim 10^{19}$ cm^{-3}, which would effectively dissociate excitons, indicating that an electron-hole plasma is the dominant gain mechanism over the entire temperature range studied (10 K to 300 K). A remarkably low lasing threshold (carrier density $< 5 \times 10^{17}$ cm^{-3}) was observed in GaN/AlGaN heterostructures over the temperature range of 10 K to 300 K. From photoluminescence studies we estimated the efficiency of carrier diffusion into the GaN active layer when carriers were generated in the well, waveguide, and cladding regions. An analysis of both the temperature dependence of the lasing threshold and the relative shift between lasing modes and spontaneous band-edge related emission indicated that the low-threshold lasing is room temperature. The implications of this study on the development of UV laser diodes will be discussed.

SESSION T4: GROWTH AND CHARACTERIZATION OF WIDE-BANDGAP MATERIALS
Chairs: Michael Wraback and James M. Van Hove
Wednesday Morning, April 26, 2000
Golden Gate A2 (Marriott)

8:30 AM T4.1
LOW TEMPERATURE LATERAL EPITAXIAL GROWTH OF SILICON CARBIDE ON SILICON.
Chacko Jacob, Shigehiro Nishino, Kyoto Institute of Technology, Dept. of Electronics and Information Science, Kyoto, JAPAN; Juyong Chung, Moon-Hi Hong, Pirouz Pirouz, Case Western Reserve University, Dept. of Materials Science and Engineering, Cleveland, OH.

To reduce the defect density inherent in conventional heteroepitaxial growth of SiC on Si, selective epitaxy followed by lateral epitaxial growth was performed in a conventional atmospheric pressure chemical vapor deposition (APCVD) system. The source gases were hexamethyldisilane (HMDS) and hexachlorodisilane (HCDS). The HCDS was added in various proportions to compensate for the excess carbon in HMDS. Hydrogen was used as the carrier gas and small amounts of hydrogen chloride (HCl) were added to improve the selectivity. Si(001) wafers, with an oxide layer (~700 nm thick) as a mask, were used as substrates. The grown films were analyzed using optical microscopy and scanning electron microscopy (SEM). Micro-Raman spectroscopy was also used to analyze various features. In earlier work[1], we had demonstrated the problems associated with the application of this technique - viz., oxide degradation, high growth temperature. Using a combination of HMDS and HCDS, the growth temperature has been considerably reduced allowing the continued use of an oxide mask. Selective growth was demonstrated in films grown at 1250°C and below. Conditions suitable for lateral epitaxial growth were also determined.
[1] C. Jacob, M-H. Hong, J. Chung, P. Pirouz and S. Nishino, Presented at the International Conference on SiC and Related Materials '99, October 10-15, North Carolina, USA.

8:45 AM T4.2
SiC EPITAXIAL GROWTH ON POROUS SiC SUBSTRATES.
G. Melnychuk, S.E. Saddow, Emerging Materials Research Laboratory, Department of Electrical & Computer Engineering, Mississippi State, MS; M. Mynbaeva, Ioffe Institute, St. Petersburg, RUSSIA; S. Rendakova, V. Dmitriev, TDI, Inc., Gaithersburg, MD.

The presence of micropipes and dislocations in SiC wafers used as substrates for SiC epitaxial growth may cause formation of lattice defects in the epilayers. The objective of this research was to develop a chemical vapor deposition (CVD) growth technique on porous SiC substrates in order to reduce the concentration of structural defects in SiC epilayers. A layer of porous SiC was formed by surface anodization of commercial 4H-SiC (0001) Si-face off-axis wafers. 4H-SiC epilayers were grown on these porous SiC substrates using atmospheric pressure CVD at 1535 C and Si to C ratio 0.3. Results of RHEED, SEM and AFM characterization demonstrated good surface quality of the films grown on porous material. Crystal structure of the grown layers was investigated using x-ray diffraction and x-ray topography. Defect density was estimated by chemical etching in molten KOH. The role of the porous structure in the epitaxial layer quality is discussed.

9:00 AM T4.3
DLTS STUDY OF 3C-SiC GROWN ON Si USING HEXAMETHYLDISILANE.
Masashi Kato, Masaya Ichimura, Eisuke Arai, Nagoya Inst of Technology, Dept of Electrical and Computer Engineering, Aichi, JAPAN; Yasuichi Masuda, Yi Chen, Shigehiro Nishino, Kyoto Inst of Technology, Dept of Electronics and Information Science, Kyoto, JAPAN; Yutaka Tokuda, Aichi Inst of Technology, Dept of Electronics, Aichi, JAPAN.

SiC is a promising material for high-power and high-frequency electronic devices. 3C-SiC can be grown heteroepitaxially on Si substrates, and this can lead to mass-production of SiC devices. However 3C-SiC/Si interface may introduce defects in epitaxial films because of large difference of thermal expansion coefficient and lattice mismatch. Usually 3C-SiC is grown by CVD method using SiH_4+C_3H_8 with H_2 carrier gas. In this work, we employ DLTS(Deep Level Transient Spectroscopy) method to characterize 3C-SiC grown by CVD using HMDS(hexamethyldisilane). This gas system has the advantages of safety and large deposition rate over the conventional gas system. To the best of our knowledge, this is the first report about DLTS of 3C-SiC grown by CVD using HMDS. Unintentionally doped n-type 3C-SiC was grown on Si(100) by atmospheric pressure CVD using HMDS at 1350°C. Thickness of epilayers were between 0.65μm and 17μm. Growth conditions were the same for all the samples expect for growth time. For DLTS measurements, planar diodes were fabricated on the samples by evaporating Au as a Schottky contact and Al as an ohmic contact. Relatively thin epilayers($\sim$2.2μm) showed broad DLTS signals over a very wide temperature range(100K$\sim$300K). These signals are attributed to defects originating from the SiC/Si interface and having activation energies distributed in a wide range. On the other hand, relatively thick epilayers(more than 2.2μm) enable us to probe SiC far away from the interface and showed only one DLTS peak near 130K. The activation energy obtained from Arrhenius plot is about 0.25eV. For 3C-SiC grown from SiH_4+C_3H_8, defects with larger activation energies of about 0.3eV have been observed.

9:15 AM T4.4
NON-CONTACT CHARACTERIZATION OF RECOMBINATION PROCESSES IN 4H-SiC. K. Matocha, T.P. Chow, R. Gutmann, Rensselaer Polytechnic Institute, Center for Integrated Electronics and Electronics Manufacturing and Center for Power Electronics Systems, Troy, NY.

Bipolar device performance metrics such as forward voltage drop, switching times, and leakage currents are significantly controlled by the carrier lifetime. To understand the behavior of carrier lifetimes in 4H-SiC, carrier recombination processes have been characterized using a non-contact microwave photoconductivity technique. A 266$\sim$nm laser beam is used to excite photons in the lightly-doped epilayer and the conductivity decay transient is measured by a 36$\sim$GHz signal coupled to the sample using a ridge waveguide. The conductivity decay on both p-type and n-type samples shows a two-stage decay mechanism to which a Shockley-Read-Hall (SRH) model has been applied. At low laser intensities, only a single exponential decay is observed. At higher injection levels, a two stage decay is present, with a slower decay followed by the same low-intensity decay. Describing this behavior with a SRH recombination model, the 10$\sim\mu$m p-type layer exhibits a high-level lifetime (τ_{HL}) of 400$\sim$ns and a low-level lifetime (τ_{LL}) of 80$\sim$ns. This corresponds to a $\tau_{p0}\sim=\sim$320$\sim$ns, and $\tau_{n0}\sim=\sim$80$\sim$ns. The 10$\sim\mu$m n-type layer also exhibits a two-stage carrier decay with $\tau_{HL}\sim=\sim$65$\sim$ns and $\tau_{LL}\sim=\sim$30$\sim$ns ($\tau_{n0}\sim=\sim$ 35$\sim$ns, $\tau_{p0}\sim=\sim$30$\sim$ns). The low-level lifetime of the p-type sample increases exponentially with temperature with an activation energy of 0.009$\sim$eV from 100-250$\sim$K, and 0.064$\sim$eV from 250-500$\sim$K. P-type epilayers on 2.0$\sim$inch wafers were observed to have longer lifetimes than those on 1.375$\sim$inch wafers. The value of high-level lifetime (0.4$\sim\mu$s) measured in this study bodes well for the development of high-voltage, fully conductively-modulated 4H-SiC devices operating at high temperatures.

10:00 AM *T4.5
GaN QUANTUM DOTS ON SAPPHIRE AND Si SUBSTRATES. Hadis Morkoc, Virginia Commonwealth University, School of Engineering and Physics Dept, Richmond, VA.

GaN dots have been grown on c-plane sapphire and (111) Si substrates by reactive molecular beam epitaxy. A method involving two-dimensional growth followed by a controlled annealing during which dots were formed was employed. Due to localization and large dot density, relatively high luminescence efficiencies were obtained on both substrates. Single layer dots were used for AFM analysis whereas 30 layer dots were used for photoluminescence experiments, the latter showing temperature dependence characteristic of strongly confined systems. AlN layers, some too thick for mechanical interaction between stacks, and some thin enough for vertical coupling were used. Strong polarization effects led to a sizeable red shift, which depends on the size of the dots. Dots showing blue (small dots) and red (large dots) shift have been prepared.

10:30 AM T4.6
OVERGROWTH OF PATTERNED $Al_xGa_{1-x}N$ NUCLEATION LAYERS ON SAPPHIRE SUBSTRATES. Roman Dimitrov, Vinayak Tilak, Michael Murphy, William Schaff, Les Eastman, School of Electrical Engineering, Cornell University, NY; Oliver Ambacher, Claudio Miskys, Alexandre Lima, Angela Link, Martin Stutzmann, Walter Schottky Institute, TU Munich, GERMANY.

The strong internal electric fields in nitride based heterostructures, resulting from charges induced at heterointerfaces by an abrupt change of their strong spontaneous and piezoelectric polarization, have a crucial effect on the electronic, and optical properties in these heterostructures. Due to polarization induced bound charges it is possible to achieve two dimensional electron gases (2DEGs) with high sheet carrier concentrations in undoped AlGaN/GaN heterostructures or to reduce the effective activation energy of the Mg-acceptor in AlGaN/GaN superlattices. The direction of the polarization and therefore the location of 2DEGs or 2DHGs in GaN/AlGaN/GaN heterostructures strongly depends on the polarity, which can be Ga- or N-face. High quality GaN grown on sapphire by MOCVD was found to be always Ga-face in opposite to GaN deposited by MBE, which polarity is N-face for material grown without nucleation layer. The polarity of MBE material can be changed to Ga-face by inserting a thin AlN nucleation layer. The structural, electric and optical properties of epitaxial GaN with N- or Ga-face polarity is found to be very different. In this study thin $Al_xGa_{1-x}N$ nucleation layers grown by PIMBE on sapphire were patterned and overgrown by MOCVD and PIMBE to obtain small regions of GaN with different polarities beside each other. In addition the use of a GaN nucleation layer with N-face polarity gives the opportunity to obtain MOCVD grown N-face GaN bulk material and N-face AlGaN/GaN heterostructures. The role of polarity on the structural and electrical properties of epitaxial layers and AlGaN/GaN heterostructures will be presented for samples grown on patterned nucleation layers with dimensions between 1 μm and 100 mm. In addition the consequences of Mg-doping during the growth by MBE on the polarity will be discussed.

10:45 AM T4.7
CRITICAL LAYER THICKNESS OF GaN/INGaN/GaN DOUBLE HETEROSTRUCTURES. M.J. Reed, N.A. El-Masry, North Carolina State University, Dept of Materials Science and Engineering, Raleigh, NC; C.A. Parker, S.M. Bediar, North Carolina State University, Dept of Electrical and Computer Engineering, Raleigh, NC.

Light emitting devices in the nitride system are based mainly on the strained GaN/InGaN/GaN double heterostructure. The thickness of the InGaN wells used in these devices is assumed to be less than the thickness at which relaxation begins. However, there have not yet been any reported data about the critical layer thickness (CLT) in these double heterostructures. We will report on an approach to determine the variation of CLT in these double heterostructures in the composition range 0<%InN<20. The approach we adopted to determine the value of CLT was to follow the evolution of the photoluminescence spectra as InGaN well thickness was increased for a given %InN. We found that the emission energy from thin InGaN wells was higher than that of thick wells due to compressive stress and possible quantum size effects. We also found that, for a given %InN, there was a sudden drop in the emission energy when the InGaN well exceeded a given thickness. The change in emission energy is nearly a step-function at a given well width that we define as the critical layer thickness of the InGaN film in the GaN/InGaN/GaN heterostructure. This is in contrast to the GaN/InGaN single heterostructure, which we observed to exhibit a gradual relaxation process. We have also observed that the photoluminescence emission intensity and FWHM of the emission spectra can be correlated to the value of the CLT. It should also be noted that the CLT's obtained in this nitride system are much higher than those predicted by the energy or force balance models. In addition, we will report on the possible relaxation mechanisms of the InGaN films and other electrical properties associated with the relaxation process

11:00 AM T4.8
SINGLE CRYSTAL GROWTH OF GALLIUM NITRIDE SUBSTRATES USING HIGH PRESSURE HIGH TEMPERATURE PROCESS. Rajiv K. Singh, D. Gilbert, F. Kelly, R. Chodelka, R. Abbaschian, S.J. Pearton, Department of Materials Science and Engineering, University of Florida, Gainesville, FL; A. Novikov, Gemesis Corporation, Sarasota, FL.

High quality bulk GaN single crystal substrates are needed to obtain low defect density homoepitaxial layers. The high temperature and pressure needed to grow GaN crystals are typically very difficult to achieve using conventional processing techniques. In this talk we have employed a unique high pressure high temperature apparatus to grow single crystal GaN substrates. The crystals were characterized by several techniques including secondary electron microscopy, x-ray diffraction, transmission electron microscopy and optical techniques. The effect of the processing conditions on the formation of the GaN crystals will be discussed.
This work is supported by a SBIR grant from BMDO.

11:15 AM T4.9
LATERAL AND VERTICAL GROWTH STUDY IN THE INITIAL STAGES OF GaN GROWTH ON SAPPHIRE WITH ZnO BUFFER LAYER BY HYDRIDE VAPOR PHASE EPITAXY. Shulin Gu, Rong Zhang, Ling Zhang and T.F. Kuech, Department of Chemical Engineering, University of Wisconsin, Madison, WI.

The initial nucleation and growth of GaN on sapphire substrates is the primary determinant of the subsequent materials properties. In the case of the Hydride Vapor Phase Epitaxy Process (HVPE), the initial nucleation behavior can be improved by the inclusion of a ZnO buffer. This buffer layer leads to the formation of a reactive diffusion couple with the underlying sapphire leading to a thin epitaxial surface layer of ZnAl2O4 with the concurrent evaporation of the unreacted ZnO film. We characterize the initial stages of growth on these ZnO-based surfaces. A high supersaturation in the growth ambient favors a rapid nucleation on the substrate. A high lateral growth rate on the surface promotes coalescence of the initial islands. Rapid coalescence leads to improved materials properties and surface morphology. These initial buffer layers and the specific flow rates of the GaCl and NH3 control these vertical and lateral growth rates. The use of a two-step growth process in the initiation of GaN growth has led to improved and controlled morphology and properties: an initial choice of conditions to promote rapid nucleation and a subsequent change in growth ambient to allow a high lateral growth rate. The results of these growth processes and the initial nucleation surface are presented.

11:30 AM T4.10
IMPROVED HETERO-EPITAXIAL MBE GROWTH OF GALLIUM NITRIDE WITH A GALLIUM BUFFER LAYER. Yihwan Kim, Sudhir G. Subramanya, Henrik Siegle, Joachim Krueger and Eicke R. Weber, Department of Materials Science and Mineral Engineering, University of California at Berkeley and Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA.

Recent advances in the quality of hetero-epitaxially grown GaN have only become possible by introduction of GaN or AlN buffer layers grown at low temperatures. In this study, we demonstrate for the first time that the usage of pure gallium (Ga) as a buffer layer results in further improvement of the quality of the GaN epilayers. Plasma-assisted molecular beam epitaxy on c-plane sapphire was employed to grow Si-doped 2 μm thick GaN epilayers after deposition of a thin Ga buffer layer. The resulting films typically show electron Hall mobilities as high as μ=400 cm^2/Vs (with a background carrier concentration of [n] = 4 x 10^{17} cm^{-3}), which represents an outstanding value for a MBE-grown GaN layer on sapphire. Also, structural properties are significantly improved; the asymmetric (101) X-ray rocking curve width is drastically reduced with respect to that of the reference GaN epilayer grown on a LT-GaN buffer layer. It is proposed that an increased stress relaxation by the soft gallium buffer layer during growth and/or cool-down is responsible for the improved material properties. This hypothesis is strongly supported by our recent study of the buffer layer composition effect on the quality of the main layer. High-resolution TEM and atomic force microscopy results are also used to study the growth mechanism of GaN on the Ga buffer layer.

SESSION T5: GROWTH AND CHARACTERIZATION OF III-NITRIDES

Chairs: Hadis Morkoc and Suzanne E. Mohney
Wednesday Afternoon, April 26, 2000
Golden Gate A2 (Marriott)

1:30 PM *T5.1
MEASUREMENT OF TRANSIT TIME AND CARRIER VELOCITY UNDER HIGH ELECTRIC FIELD IN III-NITRIDE P-I-N DIODES. M. Wraback, H. Shen, U.S. Army Research Laboratory, Sensors and Electron Devices Directorate, Adelphi, MD; J.C. Carrano, Photonics Research Center, Department of Electrical Engineering and Computer Science, U.S. Military Academy, West Point, NY.

We present the first measurement of the electron velocity at high electric fields in III-nitride materials. A femtosecond optically-detected time-of-flight technique that monitors the change in the electroabsorption associated with the transport of photogenerated carriers in a p-i-n diode has been used to determine the room temperature electron transit time and steady-state velocity as a function of electric field. For a GaN p-i-n diode grown by MOCVD with no special preparation, the transit time drops with increasing electric field in the intermediate field regime (<100kV/cm), and the electron velocity possesses a weak, quasi-linear dependence on electric field due to polar optical phonon scattering. In the high field regime the transit time and the electron velocity gradually become independent of electric field. The peak electron velocity of 1.9X10^7 cm/sec is attained at 225 kV/cm. At fields greater than 250 kV/cm, there is an apparent slight decline in the electron velocity. Our results are in qualitative agreement with a published steady-state velocity-field characteristic derived from an ensemble Monte Carlo calculation including a full Brillouin zone band structure. The fact that the peak velocity obtained from experiment is lower and shifted to higher field than its theoretical counterpart suggests that the high defect density of the device, not accounted for by theory, may play an important role in determining the velocity-field characteristic.

2:00 PM T5.2
CATHODOLUMINESCENCE OF LATERAL EPITAXIAL OVER-GROWTH GaN: DEPENDENCIES ON EXCITATION CONDITIONS. G.S. Cargill III, E.M. Campo, Lanping Yue, Dept. of Materials Science and Engineering, Lehigh University, Bethlehem, PA; J. Ramer, M. Schurman and I.T. Ferguson, EMCORE Corp., Somerset, NJ.

Yellow light (YL) emission is enhanced in comparison with near-UV (BL) emission when local current density is decreased by defocusing the electron beam in cathodoluminescence (CL) measurements on LEO GaN samples. This has generally been attributed to having limited numbers of deep level states which participate in the YL emission process. We have found that both YL and BL intensities also decrease when the scanned area is decreased, for example by increasing the magnification, although the electron beam voltage and current are held constant and similar regions of GaN are being examined. This dependence of CL intensity on scanned area may be a result of different levels of local charging for different magnification settings. Results will be presented from CL measurements on LEO GaN samples of different stripe widths and deposition conditions, together with discussions of possible explanations for the observed dependencies of luminescence on beam current, voltage, and scan parameters, in terms of the GaN materials properties.

2:15 PM T5.3
OPTICAL PROPERTIES AND CARRIER LOCALIZATION IN ALiNGaN ALLOYS. G. Tamulaitis, K. Kazlauskas, S. Jurinas, G. Kurilëik, A. Fiukauskas, M. Asif Khan, J. Yang, G. Simin, R. Gaska and M.S. Shur.

We present our results on investigation of optical properties and nonequilibrium carrier dynamics in quaternary AlInGaN materials grown on sapphire substrates by low-pressure MOCVD. Spontaneous and stimulated emission, photoluminescence excitation and time-resolved photoluminescence spectra were measured for 0.2 μm thick AlInGaN layers with 10% of Al and up to 2% of In deposited on the top of nominally undoped GaN layer. The incorporation of In resulted in the reduction of lattice constant and energy band gap of AlInGaN. We determined the optical band gap and the mobility gap of the alloy from luminescence spectra excited by irradiation of a tunable dye-laser. A very large decrease of the Stokes shift and increase of the steepness of the absorption spectra with increasing In content were observed in the photoluminescence excitation spectra. This is in a sharp contrast to the effect of In incorporation on the optical properties of InGaN. To get a deeper insight into the carrier localization process in AlGaInN, photoluminescence excitation power spectroscopy was employed. The experimental results are discussed in terms of the band-tail formation, phase separation, and internal fields due to spontaneous polarization.

2:30 PM T5.4
PHOTOCONDUCTIVITY RECOMBINATION KINETIS IN GaN FILMS. M. Misra and T.D. Moustakas, Department of Electrical and Computer Engineering and Photonics Center, Boston University, Boston, MA.

In this paper we report on photoconductivity measurements in GaN films and propose a model to account for the recombination kinetics in this material. All investigated films, grown by the plasma assisted molecular beam epitaxy method, are unintentionally doped n-type. Their resistivities were varied from 10 to 10+9 Ohm-cm by increasing the ratio of the fluxes of group V to group III during growth. We propose that this progressive transition from conductive to insulating films is due to the introduction of Ga-vacancies and/or N-antisite defects. Photoconductive detectors with interdigitated electrodes were fabricated on such films. From the measurement of photoconductive gain, the mobility-lifetime product for each film was determined. The mobility-lifetime products were found to decrease monotonically from 10-2 to 10-7 cm/V, as the dark resistivities of the films increased. We observed that this trend is also obeyed by films produced using the MOCVD method and measured in various laboratories. Thus this monotonic dependence between dark resistivity and mobility-lifetime product is independent of the method of growth of GaN films. In order to understand the dominant recombination mechanism, we studied the dependence of photoconductivity in the various films as a function of light intensity[1]. We found that the photoconductivity varies as I (power of gamma) over four orders of magnitude. Gamma was found to vary from 0.5 to 1.0, as the resisitivity of the films increased. Based on a model proposed by Rose[1], these results indicate the presence of exponential band tails extending from the conduction band edge. These results together with previously discussed dependence of recombination lifetime on the position of the dark Fermi level are analysed to derive the extent of the band tails in the films.
[1]A. Rose, Concepts in Photoconductivity and Allied Problems, Chapter 3 (Interscience Publishers,1963).

2:45 PM T5.5
OPTICAL CHARACTERISTICS OF HYDRIDE VAPOR PHASE EPITAXY (HVPE)-GROWN GaN. Eunsoon Oh, Ighyeon Kim, Sungsoo Park, Jaiyong Han, Seongkuk Lee, Kyoyeol Lee, Yongjo Park, Nitride Semiconductor Team, Samsung Advanced Institute of Technology, Suwon, KOREA.

Photoluminescence (PL) and cathodoluminescence (CL) spectra of HVPE-grown GaN samples have been studied. At 15 K, the donor-bound exciton line at 3.468 eV is dominant, whose linewidth being narrower than typical MOCVD-grown GaN. With increasing temperature another peak around 3.39 eV appears, whose relative intensity with respect to near-bandedge emission increases with increasing temperature. At room temperature these two peaks overlap with each other. In the CL spectra, we also observe a peak around 3.38 eV at 80 K. In the CL spectra its intensity was found to vary from position to position. After polishing the surface, PL intensity was drastically reduced due to the polishing-induced sub-surface damage. With the regrowth of a GaN layer on the polished surface either by HVPE or by MOCVD, the peak around 3.38-3.39 eV disappeared both in the PL and CL spectra. It was found that the CL intensity on the surface of the scatched area was stronger than that on the smooth area, indicating the incorporation of donor impurities during the polishing process. Besides the scatched areas, the CL spectra of the regrown sample were found to be much more uniform than those of the as-grown samples.

3:30 PM T5.6
EFFECTS OF INTERFACE MANIPULATION FOR MBE GROWTH OF AlN ON 6H-SiC. Koichi Naniwae, Jeff Hartman, Christian Petrich, Robert J. Nemanich, North Carolina State Univ, Dept of Physics, Raleigh, NC; Robert F. Davis, North Carolina State Univ, Dept of Material Science and Engineering, Raleigh, NC.

AlN layers were grown on 6H-SiC(0001) with various nucleation procedures, V/III ratios and substrate temperatures by MBE using ammonia. Si rich root 3 x root 3 SiC surfaces were routinely prepared by Si deposition at room temperature and annealing at ~ 900 C in the MBE chamber just before the AlN growth. C rich root 3 x root 3 SiC surfaces were also prepared using in situ annealing. RHEED was used for monitoring the surface preparation and the growth. 2-dimensional growth of AlN was observed from the very beginning for substrate temperatures in the range between ~ 800 - 900°C. The surface morphology of the AlN films observed by AFM was significantly changed by the nucleation procedure. When the growth was initiated with Al rich conditions, the surface flatness of the AlN detected by AFM was significantly enhanced while the growth rate for the vertical direction was decreased. Atomically flat AlN surfaces with a RMS-roughness ~ 0.3 nm was obtained on both types of SiC surfaces. In the case of the growth on Si rich root 3 x root 3 surfaces, Si segregation was observed on the AlN film surface by Auger Electron Spectroscopy. On the other hand, when film growth was initiated with an ammonia rich condition on Si rich root 3 x root 3 surfaces, the surface showed a high density of relatively large bumps. These features seemed to originate from SiN formation at the heteroepitaxial interface. In this case, the growth rate in the vertical direction was higher than that of the Al rich growth initialized film. It was found that the control of the Si composition and V/III ratio at the growth interface is crucial for the AlN film quality.

3:45 PM T5.7
CHARACTERIZATION OF THIN GaN LAYERS DEPOSITED BY HYDRIDE VAPOUR PHASE EPITAXY (HVPE)ON 6H-SiC SUBSTRATES. J.T. Wolan, J.T. Christiansen, Dave C. Swalm, School of Chemical Engineering; Y. Koshka, S.E. Saddow, Emerging Materials Research Laboratory, Dept. of Electrical and Computer Engineering, Mississippi State University; Yu. Melnik, V. Dnitriev, TDI, Inc. Gaithersburg, MD.

The lack of a suitable GaN substrate that is both lattice matched and thermally compatible has hindered the development of III-V nitride devices. Ideally, bulk GaN crystals would be used for substrates; however, those currently available do not exceed a few millimeters in size. SiC is an attractive substrate for epitaxial growth of GaN films exhibiting excellent lattice and thermal compatabilities. In addition, due to high SiC thermal conductivity (~ 4 W/cm-K) and cleavage possibilities, this system is particularly attractive for high-power electronic and photonic applications. Recently, thin layers of GaN on SiC have been proposed as quasi-substrate for GaN heteropitaxy. In this study, the near-surface region and outermost atomic layer of air-exposed thin GaN layers deposited by hydride vapour phase epitaxy (HVPE) on 6H-SiC substrates have been examined. Angle-resolved X-ray photoelectron spectroscopy (ARXPS), Auger electron spectroscopy (AES) and ion scattering spectroscopy (ISS) were performed. Chemical-state identification, in-depth elemental distribution profiles and outermost atomic layer compositions of the thin-films are presented. Several structure sensitive techniques including atomic force microscopy (AFM), x-ray diffraction (XRD) in ω-2θ and ω-rocking curve measurements as well as low temperature photoluminescence (PL) and scanning electron microscopy (SEM) to examine crystal structure, surface morphology and film thickness where performed and will be presented.

4:00 PM T5.8
REAL TIME OBSERVATION AND CHARACTERIZATION OF DISLOCATION MOTION, NANOPIPE FORMATION AND NITROGEN DESORPTION IN GaN. E.A. Stach and C.F. Kisielowski, National Center for Electron Microscopy, Lawrence Berkeley National Laboratory, Berkeley, CA; W.S. Wong and T. Sands, Department of Materials Science and Mineral Engineering, University of California, Berkeley, CA.

Despite the considerable attention focused on GaN in the past several years, outstanding questions remain regarding the mechanisms of defect formation. In this work, we take advantage of a recently developed processing technique known as laser lift-off to examine the behavior of thin, free-standing, nearly stress free single crystals of GaN subjected to thermal stimulus. GaN layers of 7 um thickness were removed from the sapphire growth substrate using the laser lift-off process (Wong, et al. APL, 1998) then ion milled to electron transparency. The samples were annealed at temperatures between 850 and 1025°C within the objective lens of a 200 kV transmission electron microscope, allowing real time observation of defect formation via diffraction contrast imaging. In regions free of stress, nitrogen desorption occurred along the cores of pure screw dislocations, resulting in the formation of nanopipes. In regions with small stresses, those dislocations with mixed edge and screw components were observed to glide in the three close-packed (a_1, a_2, a_3) directions, leaving behind a hollow core. At these temperatures, no motion of those dislocations with pure edge Burgers vectors was observed. The resulting defect structures have been characterized extensively with high-resolution electron microscopy and compared with structures of unannealed samples. These results yield essential insight into the process of defect formation at temperatures near those used during chemical vapor deposition growth of GaN.

4:15 PM T5.9
COMPARATIVE MAKER FRINGE ANALYSIS OF BULK AND THIN FILM GaN. N.A. Sanford, J.A. Aust, R.P. Mirin, National Institute of Standards and Technology, Optoelectronics Division, Boulder, CO; J. Torvik, J.I. Pankove, Astralux Inc., Boulder, CO.

Maker fringe analysis is a nondestructive tool that often permits the measurement of linear optical properties, non- linear optical properties, thickness, surface morphology, strain, structural orientation, and composition variation of materials supporting a second-order nonlinear susceptibility. We have performed comparative Maker fringe analysis of bulk GaN platelets grown by high-pressure processing, and thin film samples grown on sapphire by HVPE and MOCVD. Optical pumping was performed with a mode-locked Q-switched Nd:YAG laser operating at 1064 nm that produced Maker fringes at 532 nm. Multi-dimensional least-squares fitting of the fringes permitted the simultaneous solution of the refractive index and birefringence at both 1064 nm and 532 nm, and the thickness of the GaN. The scale for the SHG was set with crystalline quartz. At 532 nm the ordinary and extraordinary indices of the bulk sample were 2.405 and 2.380, respectively, and the nonlinear coefficient was a factor of 10.9 larger than that of quartz. The ordinary and extraordinary indices of the HVPE and MOCVD samples were approximately the same at 2.409 and 2.391, respectively. However, the nonlinear coefficient of the HVPE sample was 11.4 times larger than that of quartz while the nonlinear coefficient of the MOCVD sample was greater than that of quartz by a factor of 12.1. The uncertainty in the measurements of refractive index and relative nonlinear coefficients was +/- 0.001 and +/- 0.1, respectively, and consider uniformity over only a few square millimeters in all cases. The small bulk sample precluded comparisons over a larger area, however the MOCVD sample showed the least uniformity, and variations in both refractive index and nonlinear coefficient exceeded the bounds given if the sampling area increased to several square millimeters. Ongoing work involving doped GaN, tunable pumping conditions, and X-ray analysis will also be presented.

4:30 PM T5.10
TWO-DIMENSIONAL CARRIER GASES INDUCED BY SPONTANEOUS AND PIEZOELECTRIC POLARIZATION IN AlGaN/GaN HETEROSTRUCTURES. Oliver Ambacher, Martin Stutzmann, Walter Schottky Institute, TU-Munich, GERMANY; Roman Dimitrov, Brian Foutz, Joseph Smart, Jim R. Shealy, Michael Murphy, William Schaff and Les F. Eastman, School of Electrical Engineering, Cornell University, NY.

Two dimensional electron gases in $GaN/Al_xGa_{1-x}N/GaN$ heterostructures suitable for high electron mobility transistors (HEMTs) are induced by strong polarization induced effects. The sheet carrier concentration and the confinement of the two dimensional electron gases located close to one of the AlGaN/GaN interfaces are sensitive to a high number of different physical properties such as polarity, alloy composition, strain, thickness and doping of the AlGaN barrier. We have investigated the structural quality, the carrier concentration profiles and electrical transport properties of transistor structures by a combination of high resolution X-ray diffraction, atomic force microscopy, PL-spectroscopy, Hall effect, C-V profiling and Shubnikov-de Haas measurements. The investigated transistor structures with N- and Ga-face polarity were grown by metalorganic vapor phase (MOCVD) or plasma induced molecular beam epitaxy

(PIMBE) covering a broad range of alloy compositions ($0.15<x<0.6$) and barrier thicknesses between 100 and 500 Å. High electron mobilities of 1536 and 7520 cm^2/Vs were observed for sheet carrier concentrations of $1.1x10^{13}$ cm^{-2} at room temperature and 77 K, respectively.
By comparison of theoretical and experimental results we demonstrate that the formation of two dimensional electron gases in n-type intentionally undoped and Si-doped AlGaN/GaN structures both rely on the difference of piezoelectric and spontaneous polarization between the AIGaN and the GaN layer. The maximum sheet carrier concentration for undoped HEMTs with a typical barrier thickness of 300 Å is limited to about $2x10^{13}$ cm^{-2} due to strain relaxation and a reduction of piezoelectric polarization of the barrier.
In addition, the measured sheet hole concentrations in Mg-doped AIGaN/GaN heterostructures, the dependence of carrier mobility versus sheet carrier concentration will be presented and the importance of interface roughness and charged dislocation scattering on electric transport properties will be discussed.

4:45 PM T5.11
HIGH ROOM-TEMPERATURE HOLE CONCENTRATIONS ABOVE $10^{19}cm^{-3}$ IN Mg-DOPED InGaN/GaN SUPERLATTICES. Kazuhide Kumakura, Toshiki Makimoto, Naoki Kobayashi, NTT Basic Research Laboratories, Kanagawa, JAPAN.

InGaN is an attractive material for blue light-emitting diodes and laser diodes as active layers. This material is also expected to be the base layer of heterojunction bipolar transistors. While there are many reports on their optical properties of InGaN layers, there are only a few works on their electrical properties. We have previously reported on the electrical properties of p-type InGaN with hole concentrations above 10^{18} cm^{-3}. We have also reported that Mg-doped AlGaN/GaN superlattices (SLs) show higher room-temperature hole concentrations than Mg-doped GaN and AlGaN themselves. This phenomenon is ascribed to the piezoelectric charge due to the strain and the charge by spontaneous polarization in the SLs. In this work, we applied this effect to the InGaN system for the first time and grew p-type Mg-doped $In_xGa_{1-x}N$/GaN SLs with high spatially averaged hole concentrations above 10^{19} cm^{-3} at room temperature. We grew the Mg-doped InGaN/GaN SL layers by metalorganic vapor phase epitaxy at the growth temperature of 780°C on a 1-μm-thick undoped GaN layer grown at 1000°C. The layers of InGaN and GaN were the same thickness (about 4 nm), and the total thickness of the SL layers was about 0.36 μm. The doping concentration of Mg atoms for the SLs was about 3×10^{19} cm^{-3}. The hole concentrations of Mg-doped $In_xGa_{1-x}N$/GaN SLs increased with the In mole fraction, and we obtained a hole concentration of 3×10^{19} cm^{-3} at room temperature for the $In_{0.14}Ga_{0.86}N$/GaN SLs. The activation energies for Mg-doped InGaN/GaN, derived from the temperature dependence of resistivity, are about 80 and 30 meV for $In_{0.07}Ga_{0.93}N$ and $In_{0.14}Ga_{0.86}N$, respectively. These small activation energies for Mg-doped InGaN/GaN SLs result in the high hole concentrations at room temperature, indicating that almost all the Mg-acceptors are ionized and release the holes.

SESSION T6: POSTER SESSION: WIDE-BANDGAP DEVICES, MATERIALS, AND PROCESSING

Chairs: Randy J. Shul, Fan Ren, Wilfried Pletschen and Masanori Murakami
Wednesday Evening, April 26, 2000
8:00 PM
Salon 1-7 (Marriott)

T6.1
CHARACTERIZATION OF 3C-SiC FILMS GROWN BY CVD CARBONIZATION OF Si(100) SUBSTRATES. J.T. Wolan, J.T. Christiansen, Dave C. Swalm, School of Chemical Engineering; M.S. Mazzola, Emerging Materials Research Laboratory, Dept. of Electrical and Computer Engineering, Mississippi State University, Mississippi, MS.

In this study, the near-surface region and outermost atomic layer of an air-exposed thin 3C-SiC film grown on a 50-mm (2-in.) diameter Si(100) substrate has been examined. Carbonization to create the film in a RF induction-heated horizontal atmospheric-pressure chemical-vapor-deposition reactor utilized a propane-hydrogen mix (3% C3H8 in ultra-high purity hydrogen) with a hydrogen carrier[1]. Angle-resolved X-ray photoelectron spectroscopy (ARXPS), Auger electron spectroscopy (AES) and ion scattering spectroscopy (ISS) were performed. Chemical-state identification, in-depth elemental distribution profiles and outermost atomic layer compositions of the thin-film are presented. Several structure sensitive techniques including atomic force microscopy (AFM), x-ray diffraction (XRD) in ω-2θ and ω-rocking curve measurements as well as low temperature photoluminescence (PL) and scanning electron microscopy (SEM) to examine crystal structure, surface morphology and film thickness where performed and will be presented.
[1]S.E. Saddow, M.E. Okhuysen, M.S. Mazzola, M. Dudley, X.R. Huang, W. Huang and M. Shamsuzzoha, Proceedings of the Materials Research Society, Boston, MA, Nov. 1998.

T6.2
THE GROWTH AND INVESTIGATION OF SILICONE CARBIDE THIN FILMS OBTAINED BY PLASMA ASSISTED CHEMICAL VAPOR DEPOSITION. Zhozef Panosyan, Vardan Mkrttchian, Artsrun Arakelyan, Emma Arakelova, Sirvard Berberyan, Serzhik Voscanyan, Yeremia Yengibaryan, Gagik Mirzoyan, Aram Paronikyan, State Engineering University of Armenia, Yerevan, ARMENIA.

In this paper the technology of SiC thin films, grown by plasma assisted chemical vapor deposition (CVD) of partly ionized streams of hydrocarbons and their following dissolution on the single crystalline Si substrate, is described. The advantages of this method are its simplicity and the use of inexpensive and simple equipment. The source of ions, provided by reciprocally perpendicular electric and magnetic films, was used. The ions of carbon, being accelerated and focused a form the stream, directed on the Si substrate surface, where takes place the SiC layer formation. The process of hydrocarbon dissolution, as well as the density and directivity of stream may be monitored both by high external bias (1500-3000V), and by the variation of current in solenoid, where the magnetic field is created. The controlled parameter of process is also the plasma current (Ip-35-60mA), which can be influenced by the rate of flow of steams of C7H8 supplied in vacuum chamber. While the deposition process takes place, the pressure of remaining gases in chamber does not exceed ~3◇10-4 mm Hg. By using X-ray phase analysis it was shown, that obtained films are a -SiC. The thickness of films was determined by the interference of reflected from the sample surface beams. Obtained film with a thickness d=l/4n, where n is refractive index, and l the wavelength of irradiation, can be used as antireflected, protective layer on the surface of Si photovoltaic Solar cells. By using this technology based on Si single crystals, more efficient converters of solar energy into electric one were obtained, with reflection factor less than 4% at l=650 nm. In parallel, the resistance of devices towards mechanical, chemical and atmospheric influences grows, thus resulting in a longer lifetime. Also the thermo conductivity of the PV converter increases, which is very important for their operation at intensive solar radiation.

T6.3
PENDEO EPITAXY OF 3C-SiC ON Si SUBSTRATES. G.E. Carter, G. Melnychuck, S.E. Saddow, Mississippi State University, Emerging Materials Research Laboratory, Department of Electrical & Computer Engineering, Mississippi State, MS; T. Zheleva, B. Geil, K. Jones, Sensors and Electron Devices Directorate, Army Research Laboratory, Adelphi, MD.

Pendeo epitaxy of cubic SiC (3C-SiC) on (100) oriented Si substrates was conducted in a cold-wall chemical vapor deposition (CVD) reactor. First a 6 micrometer thick film of 3C-SiC was deposited using a standard growth process developed in our laboratory [1]. Next a series of stripes made from ITO were patterned using photolithography. The stripe widths varied from 5 to 8 microns in 1 micron increments. The period of the mask was 10 microns, thus the unmasked 3C-SiC on Si film dimension varied from 5 to 2 microns, respectively. A reactive ion etching process [2] was then used to etch through the 3C-SiC film and into the underlying Si substrate to a depth of 10 microns. The ITO mask was then stripped and Pendeo epitaxy growth conducted at a temperature of 1310 degrees C for 10 and 30 minutes under the following conditions: hydrogen carrier flow of 4.5 slm, Si/C = 0.25 with a silane flow of 6 sccm and propane flow of 7 sccm. (both precursor gases are 3 percent in 97 percent UHP hydrogen). After growth the samples were characterized using both SEM and TEM. The data indicate that, for the first time, Pendeo epitaxy of 3C-SiC on Si has been successfully performed. In this paper details of these preliminary experiments, including film coalescence experiments currently under way, will be discussed.
References:
[1] S.E. Saddow, M.E. Okhuysen, M.S. Mazzola, M. Dudley, X.R. Huang, W. Huang and M. Shamsuzzoha, Proceedings of the Materials Research Society, Boston, MA, Nov. 1998.
[2] G. Carter, J.B. Casady, M. Okhuysen, J.D. Scofield and S.E. Saddow, "Preliminary Investigation of 3C-SiC on Silicon for Biomedical Applications", International Conference on SiC and Related Materials (ICSCRM), Raleigh, NC, Oct. 1999.

T6.4
THE TEMPERATURE DEPENDENT BREAKDOWN VOLTAGE FOR 4H- AND 6H-SiC DIODES. You-Sang Lee, Min-Koo Han and Yearn-Ik Choi*, School of Electrical Eng., Seoul Nat'l Univ.;

Shinlim-Dong Kwanak-Ku, Seoul, KOREA. *School of Electronics Eng., Ajou Univ., Wonchun-Dong, Suwon, KOREA.

Various SiC diodes such as PN diodes and Schottky diodes in 4H- and 6H-SiC have been considerably investigated in order to find devices that exhibit high breakdown voltage and high temperature performances. However, we often see the conflict on the breakdown voltage performances and temperature characteristics even in the similar cases, which may result from the defects of SiC such as micropipe, dislocation, and deep level impurities. These also make it difficult to get the accurate impact ionization coefficients for the real breakdown voltage measurements. Therefore, it is necessary to obtain the impact ionization coefficients data from defect-free diodes. Recently, the reliable hole impact ionization coefficients of SiC were reported in various temperatures in almost ideal situation. We propose the closed-form solutions for the temperature dependent breakdown voltage for 4H- and 6H- SiC diodes in order to suggest the easy sense about breakdown voltages of any kinds of SiC diodes in an arbitrary temperature by employing the accurate hole impact ionization coefficient and by reformed impact ionization integral. This could have the identities in that previously reported other papers were the breakdown voltage analysis mainly in the non reachthrough case and they did not include the temperature factors. The main process consists of two parts. One is the parameter extraction of Fulop approximation including temperature factors M(T), from the above impact ionization coefficients. The other is the derivation of the closed form solutions for the temperature dependence of the breakdown voltage of various SiC diodes such as 4H- and 6H-SiC diode according to the SiC type and such as non-reachthrough diode (NRD) and reachthrough diode (RD) according to the electric field distribution. The good agreements between measured data and the derivated closed-form solutions were affirmed. These solutions may help the easy manual design on the SiC diode and the further devices which employ diode structures. $\int_0^W \alpha_p \exp[\int_0^x (\alpha_n - \alpha_p) dx] dx = 1$ where $\alpha_p(x,T) = M(T)|E(x)|^7$, $\alpha_n = \alpha_p/10$ and $M(T) = 4.658\times10^{-42} - 0.0079\times10^{-42}T$ (4H-SiC) $7.897\times10^{-42} - 0.0127\times10^{-42}T$ (6H-SiC) $V_B = 3.479\times10^{15} M(T)^{-1/4} N_D^{-3/4}$ (NRD) $V_B = 1.786\times10^{-1} M(T)^{-1/8} W_B N_D^{1/8} - 9.315\times10^{-8} W_B^2 N_D$ for $N_D \geq 2.812\times10^6 M(T)^{-1/7} W_B^{-8/7}$ $V_B = 9.494\times10^{-1} M(T)^{-1/7} W_B^{6/7}$ for $N_D \leq 4.058\times10^5 M(T)^{-1/7} W_B^{-8/7}$ (RD).

T6.5

A STUDY OF Pt/AlN/6H-SiC MIS STRUCTURES FOR DEVICE APPLICATIONS. Margarita P. Thompson, Dept. of Chemical Engineering, Wayne State University, Detroit, MI; Andrew R. Drews, Physics Dept., Scientific Research Laboratories, Ford Motor Company, Dearborn, MI; Changhe Huang and Gregory W. Auner, Dept. of Electrical and Computer Engineering, Wayne State University, Detroit, MI.

AlN is a promising material to replace silicon dioxide as an insulator in SiC-based devices. We present a systematic study of the electrical properties of Pt/AlN/6H-SiC MIS structures. The AlN films were deposited using Plasma Source Molecular Beam Epitaxy at substrate temperatures ranging from 500 to 800°C. The films were epitaxial to the substrate as shown by RHEED and XRD. Current-voltage and capacitance-voltage measurements were performed as a function of temperature. Most of the MIS structures showed rectifying I-V characteristics. At negative bias a drop in the capacitance is observed due to an increase in the depletion region in SiC. At forward bias, larger than 1.5 V, the capacitance decreases, in most samples, which is related to the large leakage current at forward bias. The electrical properties of the MIS structures were correlated to the deposition conditions and the structure of the AlN films. The MIS structures were tested for use as low and high temperature hydrogen and hydrocarbon sensors.

T6.6

IMPROVED SENSITIVITY SiC HYDROGEN SENSOR. C.I. Muntele, D. Ila, R.L. Zimmerman, E.K. Williams, Iulia C. Muntele, A.M. Elsamadicy, Center for Irradiation of Materials, Alabama A&M University, Normal, AL; D.B. Poker, D.K. Hensley, Solid State Division, Oak Ridge National Laboratory, Oak Ridge, TN.

Silicon carbide is intended for use in fabrication of high temperature, efficient hydrogen sensors. Traditionally, when a palladium coating is applied on the exposed surface of SiC, the chemical reaction between palladium and hydrogen produces a detectable change in the surface chemical potential. We have produced both a palladium coated SiC as well as a palladium ion implanted SiC sensor. The palladium implantation was done at 500°C into the Si face of 6H, n-type SiC at various energies and at various fluences. Then, we measured the hydrogen sensitivity response of each fabricated sensor. This was done by exposing the sensors to hydrogen while monitoring the current flow across the p-n junction(s) with respect to time. The sensitivity of each sensor was measured at temperatures between 27°C to 300°C. The response of the SiC sensors produced by Pd implantation has revealed a completely different behavior than the SiC sensors produced by Pd deposition. In the Pd deposited SiC sensors, as well as in the ones reported in the literature, the current rises in the presence of hydrogen at room temperature as well as at elevated temperatures. In the case of Pd implanted SiC sensors, the current decreases in the presence of hydrogen whenever the temperature is raised above 100°C. We will present the details and conclusions from the results obtained during this meeting.

T6.7

HALL EFFECT MEASUREMENT AT LOW TEMPERATURE OF As IMPLANTED INTO 4H-SiC. Junji Senzaki, Kenji Fukuda, Tomoyuki Tanaka, R&D Association for Future Electron Devices, Tsukuba, JAPAN; Yuuki Ishida, Yasunori Tanaka, Hisao Tanoue, Naoto Kobayashi, Kazuo Arai, Electrotechnical Laboratory, Tsukuba, JAPAN.

In order to fabricate Silicon carbide (SiC) devices, development of ion-implantation technique for selective doping into SiC is one of the significant problems because the diffusion coefficients of most dopants in SiC are negligible at temperature below 1800°C. Arsenic (As) was successfully applied as an alternative n-type dopant and the sheet resistance as low as 213 Ω/sq. was achieved in the sample, which implanted at 500°C and subsequently annealed at 1600°C with high dose. However, this value is larger than that of phosphorus implanted SiC under the same fabrication condition and very little is known about As doped SiC. Therefore, Hall measurement for As implanted SiC was investigated. As a starting material, 4H-SiC(0001) substrates with 8° off-angle and a p-type epitaxial layer were used. Ninth multiple-energy implantation (40-400 keV) was performed at substrate temperature of 500°C in order to form a box-shaped profile with depth of 0.3 mm. The total As doses were between 7×10^{14} cm^{-2} and 7×10^{15} cm^{-2}. Then, samples were annealed at 1600°C in Ar atmosphere. Following Ni electrodes evaporation, Hall effect measurements by a van-der Pauw method were carried out in a temperature range between 20K and 300K. In the high dose (7×10^{15} cm^{-2}) implanted sample, electron concentration is almost invariable with temperature. This indicates the formation of metallic conduction layer. On the other hand, samples with less than 1×10^{15} cm^{-2} dose have a temperature dependence of electron concentration. On the basis of this temperature dependence, ionization energies for As donor implanted SiC are currently analyzing using a charge neutrality equation. Detailed analysis of electrical properties will be discussed at the conference.

T6.8

METALLIZATION OF SiC BY HIGH-DOSE IMPLANTATION OF Ti, Mo, AND W IONS USING A MEVVA ION SOURCE. J.K.N. Lindner, Universität Augsburg, Institut für Physik, Augsburg, GERMANY; K. Baba, R. Hatada, Technology Center of Nagasaki, Ikeda, Omura-shi, Nagasaki, JAPAN; B. Stritzker, Universität Augsburg, Institut für Physik, Augsburg, GERMANY.

Transition metal silicides and carbides are possible candidates for future high-temperature contacts on silicon carbide. Therefore, the interaction of transition metal atoms with silicon carbide needs to be investigated. High-dose implantation of transition metal ions allows to study the solid state reaction of metal atoms with semiconductors. In particular, metallic layers with abrupt or compositionally graded interfaces and unique properties may be achieved. In this paper, the formation of transition metal silicide and carbide phases at the surface of 3C- SiC substrates upon high-dose ion implantation using a metal vapour vacuum arc (MEVVA) ion source is studied. MEVVA ion implanters provide sufficiently high beam currents to make the metallization of near surface regions by ion beams an attractive technique. Polished substrates of high-purity CVD grown poly-crystalline 3C-SiC were implanted at temperatures of 260 and 550°C with Ti, Mo, and W ions, respectively, at a constant acceleration voltage of 60 kV and with doses up to 2.3×10^{17} $/cm^2$. Samples were analyzed in the as- implanted state and after 1h vacuum annealing at temperatures between 600 and 1000°C, to determine the thermal stability of phases formed. RBS was used to analyze the depth distribution of metal atoms, XPS was applied to determine the bonding state of Si, C and metal atoms, and grazing incidence XRD was emploied to monitor the presence of crystalline phases. Cross-sectional TEM and energy filtered TEM were applied to reveal the microstructure of selected samples. Results are discussed in terms of a potential application of high-dose metal implantation for SiC metallization purposes.

T6.9

THE FORMATION AND CHARACTERIZATION OF EPITAXIAL TITANIUM CARBIDE CONTACTS TO 4H-SiC. S.-K. Lee, E. Danielsson, C.-M. Zetterling, M. Ostling, KTH, Royal Institute of Technology, Dept. of Electronics, Kista, SWEDEN, J.-P. Palmquist,

H. Hogberg, and U. Jansson, Uppsala Univ., Angstrom Laboratory, Dept. of Inorganic Chemistry, Uppsala, SWEDEN.

An important technological problem currently limiting device performance in some instances is the fabrication of high temperature stable Schottky contacts and low resistivity Ohmic contacts. For silicon carbide, many research reports have been published on electrical contacts, both Schottky and Ohmic. However, there is still a great need to continue these studies to find even better performance and practical usefulness. In this work, TiC Ohmic and Schottky contacts to 4H-SiC were formed by a new deposition method, UHV co-evaporation with Ti and C_{60}, at low temperature ($< 500°C$). We report epitaxial TiC contact formation on 4H-SiC. We achieved a contact resistivity of $2 \times 10^{-5}\ \Omega \cdot cm^2$ at 25°C for as deposited Ohmic contacts on Al ion implanted Silicon carbide. The rectifying behavior of TiC Schottky contacts was also investigated using I-V and C-V. The measured Schottky barrier height (SBH) was 1.26 eV for n-type and 1.65 eV for p-type 4H-SiC using C-V measurements for frequencies ranging from 1kHz to 1MHz. LEED, RBS, XPS, and XRD measurements were performed to analyze composition ratio, interface reaction, and structural properties of the TiC epitaxial layer.

T6.10
MICROMACHINING OF SiC WITH SHORT AND ULTRASHORT LASER PULSES. Deepak Sengupta, Kolja Nicklaus and Aravinda Kar, Laser-Aided Manufacturing, Materials and Micro-Processing Laboratory, School of Optics/Center for Research and Education in Optics and Lasers(CREOL),The University of Central Florida, Orlando, FL; Nathaniel Quick, Applicote Associates, Lake Mary, FL.

The goal of this investigation is the creation of simple defined microstructures, such as drillings, lines, circles and boxes on the surface of bulk SiC by the use of short and ultrashort laser pulses. It will be attempted to create boxes with undercuts on bulk SiC to demonstrate the ability to create volumetric structures from the surface of transparent materials. The machining of transparent materials is possible using nonlinear effects such as self-focusing, multiphoton absorption, and avalanche ionization. The structures will be checked for debris, edge quality and cracks with light, whitelight, atomic force and scanning electron microscopy. The accuracy of the structures will be discussed as a function of pulse duration (and wavelength).

T6.11
ARSENIC INCORPORATION IN GALLIUMNITRIDE GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION USING DIMETHYLHYDRAZINE AND TERTIARYBUTYLARSINE. S. Kellermann[1,2], K.-M. Yu[2], E.E. Haller[1,2] and E.D. Bourret-Courchesne[2]. [1]Department of Materials Science and Mineral Engineering, University of California, Berkeley, CA, [2]Center of Advanced Materials, Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA.

The ternary semiconductor GaNAs is attracting scientific and technical interest because of its unusually large band gap bowing. However the synthesis of this ternary alloy is difficult due to phase separation already at relatively low concentrations of N in GaAs and As in GaN as well. We present an investigation of the incorporation of small concentrations of As (up to the percent range) into GaN grown by MOCVD using the novel liquid precursor dimethylhydrazine (DMHy) as source of nitrogen. Tertiarybutylarsine (TBA) and triethylgallium (TEG) were the other source materials. Device-quality GaN grown by MOCVD commonly uses ammonia as N-source which usually requires reaction temperatures of more than 1000°C and molar flow ratios [V]/[III] of around 5000. DMHy is already fully decomposed at the relatively low temperature of 700°C resulting in a more efficient growth process. The GaN layers doped with As were grown at 800 and 900°C and with molar flow ratios [As]/[V] ranging from 0.012 to 0.1. They were deposited on top of an undoped GaN layer and then capped with a thin undoped GaN layer also grown at 980°C with a [V]/[III] ratio of 57. Secondary ion mass spectroscopy (SIMS) data reveal a strong decline in As incorporation with increasing growth temperatures from 800°C to 900°C. Changing the [As]/[V] ratio from 0.012 to 0.057 leads to an increased As concentration in the GaN layers. However growth is progressively inhibited resulting in declining growth rates. At an [As]/[V] ratio of 0.01 the growth appears to proceed very slowly and phase separation is present for the low temperature case. The structural and optical properties of these films obtained by SIMS, Rutherford backscattering spectrometry (RBS), photoluminescence (PL), x-ray diffraction (XRD) and Hall effect measurements will be discussed.
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T6.12
PENDEO-EPITAXY OF GaN ON Si SUBSTRATES-A FINITE ELEMENT ANALYSIS. Waeil Ashmawi*, Tsvetanka Zheleva and Kenneth A. Jones. *North Carolina State University, Department of Mechanical Engineering, Raleigh, NC, US Army Research Laboratory, SEDD, Adelphi, MD.

The advances in the blue laser diodes in the past few years unambiguously proved the role of defect reduction for the quality and lifetime of the devices via the control of the lateral epitaxial overgrowth of GaN. Pendeo-epitaxy of GaN on 6H-SiC substrates followed as an alternative to the conventional LEO technique, via etching columns along 1-100 direction in the underlying GaN layer[1]. However, it is still not clear the role of the stress distribution during the growth and on cooling, as well as it's role for the difference in the dislocation density distribution within the structures. It was shown that pendeo epitaxy of GaN can be achieved not only on 6H-SiC, but on Si substrates, as well[2]. The present study uses Finite Element Approach for stress analysis of pendeo-epitaxial GaN structures, on Si substrate and utilizing transformation 3C-SiC layer. The model uses symmetric boundary conditions along the 11-20 side walls, and far end boundary conditions for the bottom of the heterostructure. Stresses and strains are evaluated considering Hookean elasticity model, fixed elastic constants and considering only the mismatches in thermal expansion coefficients among the phases in the hetero-structures. A transformation of the elastic tensor for Si was performed in order to account for the differences of the orientation between the films and the Si substrate. The range in stresses varies from -4.2 GPa (compressive) to 0.4 GPa (tensile) along [11-20] direction, and from -0.9 GPa to 0.3 GPa along [0001]. The stress gradients are localized at the bottom of the GaN column regions at the interface with the AlN/3C-SiC/Si interfaces.
[1]T. Zheleva et al., J. Electr. Mater. 28, L5 (1999).
[2]K. Linthicum et al., Internet, J. Nitride Semicond. Res. 4S1, G4.9 (1999).

T6.13
p-GaAs BASE REGROWTH FOR GaN HBTs AND BJTs. G. Dang, A.P. Zhang, X.A. Cao, F. Ren, S.J. Pearton, H. Cho, University of Florida; J.M. van Hove, J.J. Klaassen, C.J. Polley, A.M. Wowchack, P.P. Chow, D.J. King, SVT Associates; W.S. Hobson, J. Lopata, Bell Laboratories, Lucent Technologies.

Low resistance ohmic contacts are difficult to form to p-type GaN and AlGaN due to the unavailability of growth methods for highly p-doped GaN and AlGaN. p-type carbon-doped GaAs regrowth on p-GaN prior to ohmic metallization has been shown to improve contact resistance in p-GaN. Applying the regrowth method to the p-base regions of npn bipolar transistor structures, AlGaN/GaN Heterojunction Bipolar Transistors and GaN Bipolar Junction Transistors have been demonstrated. GaN/AlGaN epilayers were grown with a Molecular Beam Epitaxy system. Highly doped p-GaAs ($10^{20}\ cm^{-3}$) was grown on the devices ($\sim$500 Å) by Metal Organic Chemical Vapor Deposition after emitter mesa etching. Emitter and base mesa structures were formed by Inductively Coupled Plasma etching under low damage conditions with a Cl_2/Ar chemistry. SiO_2 was used for emitter sidewall formation to reduce leakage current to the emitter. Very high current densities were obtained for common base operation in both device types. The devices were also operated at 250°C.

T6.14
GROWTH OF HIGH QUALITY GaN USING THE LOW-TEMPERATURE INTERMEDIATE LAYER. M. Benamara, Z. Liliental-Weber, E. Bourret, J.H. Mazur, W. Swider and J. Washburn, E.O. Lawrence Berkeley National Laboratory, Berkeley, CA.

Growth of thick GaN at low-temperature (LT) is characterized by an island growth with an highly defective layer. When a subsequent GaN layer is deposited at high-temperature on top of this LT-GaN layer, lateral growth takes place in between islands. The goal of this growth method is to improve the quality of HT-GaN layer since it bends over dislocations horizontally so that most of them originating from the LT-GaN layer will end at voids separating the islands. This leads to a GaN material above voids with an excellent crystalline quality. Based upon Burgers vector analysis of dislocations in the vicinity of islands and in the HT-GaN layer, the efficiency of the LT-GaN layer is presented and discussed. An objective of this analysis is to correlate the island distribution and the defect density in the HT-GaN layer. While increasing the growth temperature of the HT-GaN layer does not change its overall structural aspect in terms of defect density, a decrease of the average island thickness of the LT-GaN layer results in a significant reduction of dislocations in the subsequent HT-GaN films.

T6.15
TRANSIENT PHOTORESPONSE FROM SCHOTTKY BARRIERS ON AlGaN. R. Schwarz, M. Niehus, L. Melo, P. Brogueira, S. Koynov, Physics Department, Instituto Superior Técnico, Lisbon, PORTUGAL; M. Heuken, Aixtron GmbH, Aachen, GERMANY;

D. Meister, B.K. Meyer, I. Physics Department, University of Giessen, Giessen, GERMANY.

Different metals like Co, Cr, In, and Cu deposited on undoped AlGaN alloy samples with Al content between 2.5 and 18% were used for testing the temporal behavior of Schottky barrier detectors in the visible and UV spectral range after pulsed laser excitation. For comparison, the same samples were also analyzed in the secondary photocurrent mode were it is known that persistent photoconductiviy affects the detector performance and slow detector response [1]. The samples were prepared by metal-organic vapor phase epitaxy (MOVPE) on sapphire substrates. Co and Cu with a thickness of about 20 nm were deposited by plasma-induced sputtering. The films were characterized by temperature-dependent dark conductivity, photocurrent and photoluminescence spectroscopy, and Hall measurements. The carrier densities at room temperature range from $3x10^{16}$ to $4.6x10^{18}$ cm^{-3} depending on Al content. The surface structure of the bare films and the metal contacts were analyzed by AFM. Carriers were generated with green (532 nm) and UV (266 nm) pulses of a Nd:YAG laser system. The secondary photocurrent transients showed a slow decay reaching the ms time region after both green and UV laser excitation [2]. Apart from small lateral effects near the contacts no signal at zero applied bias is seen. In the primary photocurrent mode the Schottky barrier in the 18% Al content alloy sample manifests itself with a fast initial decay time of about 2 microseconds. Contrary to expectations, also In and Al showed a clear Schottky barrier behaviour with band bending downwards towards the interface. The barrier height is substantially lowered in the low Al content sample due to its higher carrier concentration.

[1] M. Razeghi et al., J. Appl. Phys. 97 (1996) 7433.
[2] D. Meister et al., 3rd Int. Conf. On Nitride Semiconductors (ICNS-3), Nice, 1999.

T6.16

COMPARISON OF DIFFERENT SUBSTRATE PRE-TREATMENTS ON THE QUALITY OF GaN FILM GROWTH ON 6H-, 4H-, AND 3C-SiC. K.H. Lee, M.H. Hong, K. Teker, P. Pirouz, Case Western Reserve University, Department of Materials Science and Engineering, Cleveland, OH.

Together with sapphire, SiC is the promising substrate material for GaN epitaxial growth. In fact, SiC has advantages over sapphire because of its better thermal conductivity and lower film/substrate lattice mismatch(~3.5%). However, nucleation of GaN on SiC is rather difficult because of the low surface energy of SiC and the sensitivity of substrate preparation. This latter point makes it essential to use a very careful cleaning step, and also to pre-treat the substrate surface by growing a thick high-temperature buffer layer of AlN. In this study, several pre-treatment steps of SiC for GaN deposition were tested including (a)pre-nitridation with NH3 for 0.5-20 min., (b)pre-adsorption of TMG or TMA for 0.5-5 min, and (c)deposition of AlN buffer layers of different thicknesses at 1100-1150C. After each pre-treatment, GaN was deposited by MOCVD using dilute H_2 (Ar + 12%H_2) and TMG. After nitridation of SiC, only a polycrystalline GaN was formed on the substrate. In case of pre-adsorption of TMG, epitaxial but island-like GaN was deposited. In the third case, with an ultra-thin (~1.5 nm) coverage of AlN on SiC (by pre-adsorption of TMA or by 50 sec deposition of AlN), GaN epilayers were successfully deposited on SiC. All the films were characterized by XRD and cross-sectional TEM. When AlN was deposited for longer than 3 min.(up to 10 min.), only polycrystalline GaN was obtained. With this technique of covering the surface with an ultra-thin layer of AlN, epitaxial GaN has been successfully deposited on 6H-SiC (0001), 4H-SiC(0001), and 3C-SiC/Si(111) substrates. The effect of the different pre-treatments of SiC on the quality of the deposited GaN films will be discussed and compared, and the optimal conditions for GaN deposition for each substrate will be presented.

T6.17

RHEED PATTERN OF GaN GROWN ON 6H-SiC BY MO-MBE USING MOVPE-GROWN AlGaN. Tohru Honda, Tomohiro Takezawa, Youichi Yamamoto, Kyousuke Maki and Hideo Kawanishi, Dept. of Electronic Engineering, Kohgakuin Univ., Tokyo, JAPAN.

The lattice constants of GaN layers along the a-axis were estimated using RHEED patterns during metal-organic molecular beam epitaxy (MO-MBE) growth. Triethylgallium and ammonia were used for the gallium and nitrogen sources, respectively. The GaN layers were grown on 6H-SiC with and without AlGaN layer grown by metal-organic vapor phase epitaxy (MO-VPE). The lattice relaxation of GaN layers was observed during the initial growth in both cases. The crystal structure changed from the mixed (cubic and hexagonal) to the hexagonal phase at the direct growth of GaN. On the other hand, the hexagonal crystal structure maintained during the growth using the AlGaN buffer layer grown by MOVPE. The RHEED patterns of GaN grown on the AlGaN buffer were streaky, but, in contrast, those of GaN without any buffer layer were spotty. These may be due to the polarity of GaN layer and/or the steps on the 6H-SiC substrate. It was reported (M. Sumiya et al., APL75, 624) that the (0 0 0 1) GaN layers (Ga face) grown by MO-VPE were a smooth surface. In contrast, there were hexagonal facets on the rough surface of (0 0 0 - 1) GaN layers (N face). The RHEED patterns were consistent with these reported results. In initial growth of GaN on 6H- SiC without any buffer layer, the mixture of cubic and hexagonal phase was observed in RHEED patterns. This may be due to the surface of 6H-SiC with steps, which have cubic and hexagonal sub-unit cells. Those mixture phases indicate that there were the stack ing faults on the layers.

[1] M. Sumiya, M. Tanaka, K. Ohtsuka, S. Fuke, T. Ohnishi, I. Ohkubo, M. Yoshimoto, H. Koinuma and M. Kawasaki, Appl.

T6.18

DISLOCATIONS IN DEFORMED GaN THIN FILMS. M.H. Hong, P. Pirouz, Department of Materials Science and Engineering, Case Western Reserve University, Cleveland, OH; D.R. Clarke, Engineering III, University of California-Santa Barbara, CA.

AlN, GaN, InN and alloys of them are wide bandgap semiconductors showing considerable promise for optoelectronic applications. However, in spite of the widespread interest in these materials, their deformation behavior and microstructure have not been studied in sufficient detail partly because they are not readily available in bulk form. Using the technique of hydride phase vapor epitaxy (HPVE), it is possible to grow relatively thick single crystal GaN films (with a thickness of 100μm or more). We have employed such HPVE GaN crystals and investigated their indentation behavior as a function of temperature and load. In a previous study [1], it was reported that Vickers indentation of the [0001]-oriented GaN thin films produced a dense array of straight screw dislocations along the three $\langle 11\bar{2}0 \rangle$ directions on the prism planes. In the new experiments, the (0001) and $1\bar{1}00$ faces of an HPVE GaN crystal were deformed by Vickers indentation over a range of temperatures from 25 to 800°C. Following the indentations, the defect microstructure of the deformed crystals was investigated by transmission electron microscopy (TEM). In all cases, the stress-induced dislocations had a Burgers vector of $b=1/3\langle 11\bar{2}0 \rangle$. Interestingly, when the$1\bar{1}00$ face of the GaN crystal was indented, dislocations were generated from the indentation site on the prism planes. Such dislocations were not dissociated within the resolution of weak-beam TEM. In addition, in contrast to the very straight dislocations on the (0001)-indented face, the dislocations generated by indenting the $1\bar{1}00$ face were curved in the shape of half-loops emanating from the indentation site. This indicates that the Peierls energy on the prism plane of GaN is much lower as compared to the basal plane. These results will be discussed and compared with deformation-induced dislocations in other semiconductors.

[1] M.H. Hong, A.V. Samant, V. Orlov, B. Farber, C. Kisielowski and P. Pirouz, Deformation Dislocations in 4H-SiC and GaN, in Proceedings of the Symposium on Wide-Bandgap Semiconductors for High-Power, High-Frequency and High-Temperature Applications - 1999, edited by S. Binari, A. Burk, M. Melloch and C. Nguyen (Materials Research Society, Volume 572, Pittsburgh, PA, 1999), pp. 369-375.

T6.19

MOCVD GROWTH AND MAGNETO-TRANSPORT STUDIES OF AlGaN/GaN HETEROSTRUCTURES GROWN ON SAPPHIRE SUBSTRATES. Tao Wang, D. Nakagawa, J. Bai, S. Sakai, Satellite Venture Business Laboratory, Department of Electrical and Electronic Engineering, University of Tokushima, JAPAN; Y. Ohno, H. Ohno, Laboratory for Electronic Intelligent Systems, Research Institute of Electrical Communication, Tohoku University, Sendai, JAPAN.

Temperature-dependent magneto-transport measurements were carried out on high quality two dimensional electron gas (2DEG) in nominally undoped AlGaN/GaN heterostructure with a low temperature mobility of over 10^4 $cm^2/V.s$ grown on sapphire substrates[1]. The GaN electron effective mass and the quantum scattering time are determined by well-resolved Shunbikov-de Hass oscillation. The electron effective mass is determined to be $19m_0$ and $0.24m_0$ for the 2DEG in $Al_{0.18}Ga_{0.82}N$/GaN single heterostructure (SH) and $Al_{0.10}Ga_{0.90}N$/GaN SH, respectively. This difference of the electron effective mass probably results from the piezoelectric effect, which in turn strongly depends on Al content. The ratio of the classic scattering time to the quantum scattering time increases with increasing 2DEG sheet carrier density, which agrees very well with the previous calculation based on an ideal 2DEG in conventional semiconductor systems. Our result indicates that a low density of deep centers maybe result in this much higher mobility of our structure compared with other reports, which is probably a key to obtain high quality of 2DEG structure in AlGaN/GaN system. This result can also well explain our previous report that the mobility dramatically decreases if the AlGaN layer is doped by silicon[2].

1. T.Wang et al, App.Phys.Lett. **74**, 3531 (1999).
2. T.Wang et al, J.Crys.Growth **203**, 443 (1999).

T6.20
FORMATION AND CHARACTERIZATION OF OXIDES ON GaN SURFACES. D. Mistele, T. Rotter, F. Fedler, H. Klausing, O.K. Semchinova, J. Stemmer, J. Aderhold and J. Graul, Laboratory for Information Technology, University of Hanover, GERMANY.

We have characterized oxides which can be formed directly on n-GaN surfaces. The methods used for oxide layer formation were both photoelectrochemical processing and annealing in O_2-atmospheres at varying temperatures. These methods avoid interface traps which would be introduced e.g. by sputtering.
The photoelectrochemical oxidation takes place in aqueous solution of potassium hydroxide for pH values $\leq$ 12.5. HeCd laser light (325 nm) generates the holes and electrons necessary for the substitution reaction at the GaN/electrolyte interface. The formation of oxide layers is controlled via a potentiostat in the 3 electrode configuration. Homogenous oxide films have been obtained in the voltage range from -0.6 V to 0.4 V vs SCE (saturated calomel electrode). These layers are soluble ex-situ in alkaline or acid solutions or can also be dissolved in-situ.
The characterization of the oxide layers has been performed by Auger-electron-spectroscopy. First the surface chemistry has been determined, proving that Ga-oxide is formed with an attributed stoichiometry of Ga_2O_3. Secondly, depth profiling by Ar sputtering shows the oxide thickness to be dependent on the photoanodic voltage. Additionally, an energy shift of the Ga $M_2M_{4,5}M_{4,5}$ Auger-electron peak to lower values has been detected for all Ga-oxide layers compared to untreated GaN surfaces and pure gallium. These results make clear that the chemical bonds have changed and the results are in good agreement with the oxide layer found on anodized GaP [1]. Annealing GaN in O_2-atmospheres above 900°C also leads to surfaces fully covered with Ga_2O_3. We found that N-polar surfaces oxidize faster than Ga-polar surfaces, which is in agreement to the recent theoretical work of Zywietz[2].
The usage of these oxide layers as dielectrics will be discussed.
[1] A. Okada et al. Appl. Phys. Lett. 39 (5), 447 (1978).
[2] T. Zywietz et al. Appl. Phys. Lett. 74 (12), 1695 (1999).

T6.21
FERMI LEVEL POSITION AT THE AlGaN SURFACE IN AlGaN/GaN 2DEG HETEROSTRUCTURES. Roberta Lantier, Angela Rizzi, and Hans Lüth, ISI Forschungszentrum Jülich, Jülich, GERMANY.

By means of *in situ* photoemission spectroscopy the Fermi level position at the AlGaN surface has been determined. The AlGaN/GaN heterostructures have been grown on SiC(0001) by MBE with a RF plasma source for the activated nitrogen supply. The thickness of the AlGaN top layer is 25 nm and two Al concentrations have been considered, 14% and 41%. These are typical values for 2DEG heterostructures designed for HEMT applications. The valence band photoemission spectra have been measured by XPS after transferring the sample under ultra high vacuum conditions from the MBE into the XPS unit. The measured spectra have been fitted close to the valence band maximum (VBM) to give an accurate energy position of the VBM. The obtained results are: E_F-VBM=(2.7±0.1) eV at the $Al_{0.14}Ga_{0.86}N$ and E_F-VBM=(2.8±0.1) eV at the $Al_{0.41}Ga_{0.59}N$ surfaces. After exposure to the atmosphere the XPS valence band spectrum of the sample with the higher Al content has been measured and E_F-VBM=(2.9±0.1) eV, showing a movement of the Fermi level towards the conduction band. A clear change of the energy distribution curve close to the VBM is also observed, corresponding to a change in the surface state density of the AlGaN after exposure to air. Electrical measurements, Hall effect and CV profiling, have been also performed and the results are correlated to the information on the boundary conditions and on the macroscopic polarization fields in the AlGaN/GaN heterostructure, as gained by the XPS experiments.

T6.22
ACHIEVEMENTS AND CHARACTERIZATIONS OF GaN FILMS WITH Ga-POLARITY IN RADIO-FREQUENCY PLASMA-ASSISTED MOLECULAR BEAM EPITAXY. Xu-Qiang Shen, Toshihide Ide, Sung-Hwan Cho, Mitsuaki Shimizu, Shiro Hara and Hajime Okumura, Materials Science Division, Electrotechnical Laboratory, Tsukuba, Ibaraki, JAPAN.

Recently, lattice polarity in III-nitride films becomes a hot topic due to its great influence on the optical and electrical properties of the films. Characterizations by CBED, HSXPD, chemical etching and RHEED indicated that Ga-polarity films were always obtained from samples grown by MOCVD, while the lattice orientation of conventional MBE-grown sample is assumed to be mainly N-face. In III-nitride materials, MBE-grown films usually show poor qualities compared with MOCVD-grown ones, especially concerning electrical properties. Recently, we pointed out that the growth should be done under the Ga-face mode to get high film qualities in MBE. Therefore, realizing GaN films with Ga-face polarity in MBE growth becomes an important subject. In this study, we investigated film polarities and qualities of GaN films concentrating on the use of different buffer layer processes at the initial stage by rf-MBE. Low temperature (LT=500°C) and high temperature (HT=700°C) GaN and AlN buffer layers were performed at the initial growth stage. Direct clarifying by coaxial impact collision ion scattering spectra (CAICISS) technique, together with RHEED, surface morphology observations and chemical wet etching, were applied to identify the surface polarity of GaN films. XRD, PL and Hall-effect measurements were carried out to characterize the qualities of GaN films. As a summary, we succeeded in realizing GaN films with Ga-face lattice polarity by using AlN high temperature (HT=700°C) buffer layer in rf-MBE. XRD rocking curve showed that the FWHM of GaN film with Ga-polarity was decreased to about half of that with N-polarity. Hall effect measurement results indicated that the mobility of the Ga-face film was increased to one order higher than that of N-face one. This is a promising result and is expected to give a breakthrough for getting high quality III-nitride films by MBE for device applications.

T6.23
NATURE OF THE FLICKER AND GENERATION-RECOMBINATION NOISE IN n-TYPE GALLIUM NITRIDE. Changfei Zhu, W.K. Fong, B.H. Leung, C.C. Cheng and C. Surya, Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, HONG KONG.

Low frequency noise is investigated in n-GaN film grown by rf-plasma assisted molecular beam epitaxy. The temperature dependence of the voltage noise power spectra Sv(f) was examined from 400K to 90K in the frequency range between 80Hz and 50KHz. The Sv(f) dependence can be modeled as the superposition of 1/f (Flicker) noise and a Lorenzion (G-R) noise. For the Flicker noise the Hooge constant is about 4, which indicates that the noise level in GaN is rather high. It is suggested that the nature of the Flicker noise in n-type GaN be caused by the fluctuations of the occupancy of the tail states near the band edges, and the G-R noise should be correlated to capture and emission of electrons by single level traps. The Arrhenius fit of the fluctuation time constant indicates the G-R noise arises from trap on energy level of 119meV from the band edge.

T6.24
MONTE CARLO BASED CALCULATION OF TRANSPORT PARAMETERS FOR WIDE BAND GAP DEVICE SIMULATION. Enrico Bellotti, Maziar Farahmand, School of ECE, Georgia Tech, Atlanta, GA; H.-E. Nilsson, Dept. of Information Technology, Mid-Sweden University, Sundsvall SWEDEN; Kevin F. Brennan, School of ECE, Georgia Tech, Atlanta, GA; Paul P. Ruden, Dept. of ECE, University of Minnesota, Minneapolis, MN.

In this paper, we present Monte Carlo based calculations of transport parameters useful in the simulation of III-nitride and SiC based devices. The calculations are performed using a full band ensemble Monte Carlo model that includes numerical formulations of the phonon scattering rates and impact ionization transition rates. Calculations are made for the wurtzite and zincblende phases of GaN, the wurtzite phase of InN, and the 3C (cubic) and 4H phases of SiC. The basic transport parameters determined are the carrier mobility, saturation drift velocity, field dependent mobility model, ionization coefficients and average carrier energies as a function of applied electric field. A relative comparison of the device potential of these devices is also presented.

T6.25
DESIGN CONSIDERATIONS FOR AlGaN/GaN HETEROJUNCTION BIPOLAR TRANSISTOR STRUCTURES. Yumin Zhang, Cheng Cai, P. Paul Ruden, Univ of Minnesota, Dept of Electrical and Computer Engineering, Minneapolis, MN.

The potential of III-Nitride materials for the fabrication of bipolar transistors is investigated theoretically. Several different AlGaN/GaN based n-p-n heterojunction bipolar transistor structures are examined through calculations of their band profiles and majority carrier distributions in equilibrium and in forward active mode. A critical issue for the successful design of these types of devices is to overcome limitations on the achievable hole concentrations imposed by the relatively deep acceptors that form in the III-Nitride materials. In this work, spontaneous and piezoelectric polarization charges are utilized to create large hole sheet densities in the base layer, thus minimizing the base spreading resistance. At the same time, a built-in, large accelerating field in the base can help reduce the base transit times of the electrons and, hence, increase the current gains of these devices. The band profile and majority carrier concentrations of several AlGaN/GaN HBT structure are calculated self-consistently in a semi-classical approximation taking into account the polarization charges, charges associated with ionized donors and acceptors, and majority carrier charges. Two novel structures with the common feature that the AlN mole fraction is graded up in the emitter then graded down in the base are proposed. These structures require only a relatively thin strained layer, thus the possibility of strain relaxation is minimized. In order to suppress hole injection into the emitter effectively, a multi-layered structure in which both composition and doping are modulated is proposed for the emitter base junction region.

T6.26
THERMAL MODELING OF III-NITRIDE HETEROSTRUCTURE FIELD EFFECT TRANSISTORS. T. Li, P.P. Ruden, Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN; J.D. Albrecht, M.G. Ancona, Electronics Science and Technology Division, Naval Research Laboratory, Washington, DC.

The output characteristics of III-Nitride semiconductor heterostructure field effect transistors (HFETs) are strongly dependent on the ambient temperature of the channel region due to relatively large variations in the electron drift velocity with temperature. If the devices are optimized for high output power, the channel region acts as a significant heat source. To maintain acceptably low ambient temperatures effective heat sinking of the device appears to be critical. Heat sinking can be accomplished either through the substrate or through the contacts of the device by implementing a suitable flip-chip bonding process. The first option is impeded by the relatively low thermal conductivity of sapphire, which is the standard substrate material. (The alternative substrate, SiC, offers significant advantages). In this paper several options for effective heat sinking of AlGaN/GaN HFETs on sapphire and SiC substrates are examined by modeling the heat flow in different device designs using two- and three-dimensional finite element calculations. The model developed for this work incorporates the non-linearity of the problem arising from the temperature dependencies of the III-Nitride and substrate thermal conductivities through the technique of self-consistent boundary conditions. The results of the thermal model are then used to calculate the DC output characteristics of several different device designs. It is shown that improvements in thermal management can have a large positive impact on the power performance of III-Nitride HFETs.

T6.27
CHARACTERISTIC OF OPTICAL PROPERTY AND DEFECT ANALYSIS IN InGaN-BASED LIGHT EMITTING DIODES. C.F. Lin, H.C. Cheng, Department of Electronics Engineering and Institute of Electronics & Semiconductor Research Center, National Chiao Tung University, Hsinchu, TAIWAN ROC; G.C. Chi, Department of Physics, National Central University, Chungli, TAIWAN ROC.

The material and device properties of InGaN/GaN double heterostructure (DH) and multiple quantum wall (MQW) LED structures were studied. The characteristics of PL and electro- luminescence (EL) spectrums of both structures were measured by various the pumping laser power and injection current, respectively. The blue emission peak of PL spectra from InGaN:Zn DH structure and InGaN MQW were appear at 470nm and 433nm and their FWHM are 28nm and 40nm at 11mW laser excitation power. The blue peak of InGaN:Zn DH structure blue peak had the blue shift phenomenon while pumping power increasing. The EL intensity of 420nm peak (band-edge emission of InGaN) increased and the 470nm peak (Zn-acceptor states) saturated with the high injecting DC current in DH-LED structures. The EL intensity of 420nm peak (band-edge emission of InGaN) increasing and the 470nm peak (Zn-acceptor state) saturated with the high injected current, and the EL intensity ratio of 420nm/470nm peaks were raised by increasing the injection current. In MQW-LED structures, the EL spectrums at 457nm with 28nm linewidth shown the high quality of optical confinement. And the blue shift of EL spectra in InGaN well by increasing the injection current were due to the band filling effect. When an AC voltage is applied the defect levels in the depletion region of both LED structures, the imaginary capacitance were measured by the admittance spectroscopy attributed from the total defect density in the active layers. The sheet defect density (Ddf) of the active layers are calculated as the values 4.5E9 cm^{-2} and 6.4E8 cm^{-2} for DH-LED and MQW-LED compared with the output power were 100mW and 700mW at 20mA.

T6.28
LONG TIME-CONSTANT TRAP EFFECTS IN AlGaN/GaN HFETS. Xiaozhong Dang, Peter M. Asbeck, Edward T. Yu, University of California, San Diego, Dept. of Electrical and Computer Engineering, La Jolla, CA; Gerry J. Sullivan, Rockwell Science Center, Thousand Oaks, CA; Karim S. Boutros, Joan M. Redwing, Epitronics/ATMI, Phoenix, AZ.

AlGaN/GaN HFET's have attracted intense research interest due to their demonstrated performance and outstanding potential for operation at high power, high temperature and high frequency. Despite the attainment of extremely high power densities and total power at microwave frequencies, the microwave power densities reported are often lower than those that would be expected based on measured DC current-voltage characteristics. A detailed assessment of these effects and their possible origin in material properties, e.g., traps, is required for optimization of microwave device performance[1]. In this work, transient current response to pulsed gate and drain bias voltages have been measured and compared to DC current-voltage characteristics in AlGaN/GaN HFET's. Measurements under pulsed conditions yield current levels significantly lower than those obtained under DC conditions, and time-resolved measurements reveal substantial gate and drain lag effects with time constants varying from several to hundreds of seconds. Measurements under a wide range of bias voltage conditions combined with an assessment of the influence of illumination indicate that the trap levels primarily responsible for gate lag are located near the channel and in the GaN buffer layer or at the AlGaN/GaN interface. Drain lag appears to arise largely from traps at or near the AlGaN surface, and measurements in heavily doped devices suggest that these effects may be screened by dopants in the AlGaN barrier.
*Support for this work was provided by BMDO (Dr. Kepi Wu) monitored by USASMDC.
1. Steven C. Binari, 1999 IEEE MTT-S International Microwave Symposium Digest, Piscataway, NJ, Vol. 3.4, pp.1081 (1999).

T6.29
AlGaN/GaN HEMTs WITH EXTREMELY SHORT GATE LENGTH. Oliver Breitscädel, Hedi Gräbeldinger, Bertram Kuhn, Ferdinand Scholz, Heinz Schweizer, 4. Physikalisches Institut, Universität Stuttgart, Stuttgart, GERMANY.

AlGaN/GaN based high electron mobility transistors (HEMTs) have demonstrated excellent high frequency performance at high power and high temperature. To achieve high speed operation with transistors the time constant of the RC-circuit (R represents the gate resistance and C the gate capacitance) should be as low as possible. The value of the capacitance is essential determined by the gate length of the device. Therefore the gate resistance has to be kept low while simultaneously reducing the gate length. This can be done by forming a T-shaped gate. We have fabricated AlGaN/GaN HEMTs with gate lengths from 250 nm down to 70 nm to study DC- and high frequency characteristics of short channel devices. The 70 nm devices are, to our knowledge, the shortest gate length realized in this material system. For our devices we have grown nominally undoped AlGaN/GaN heterostructures with low pressure MOCVD on (0001)sapphire substrate. The GaN layer has a thickness of about 1 μm followed by a AlGaN channel layer with a thickness of about 50 nm with an Al concentration of 18%. The devices were fabricated using a high resolution electron-beam lithography system. For the 70 nm T-gate we have developed a 3-layer e-beam resist technique. The 70 nm device has a maximum drain current density of about 700 mA/mm and can be completely pinched off. The breakdown voltage is 27 V and the maximum extrinsic transconductance is 155 mS/mm which is nearly a factor of 4 higher than the transconductance of a device with 2 μm gate length on the same wafer and shows the high performance of our short channel device. The cutoff frequency and the maximum oscillation frequency, both obtained from S-parameter measurement, is 43 GHz and 100 GHz, respectively.

T6.30
PLASMA-INDUCED DAMAGE AND PASSIVATION OF GaN In ELECTRON CYCLOTRON RESONANCE EXCITED N_2 PLASMA SOURCE. J.T. Hsieh, O. Breitschädel, M. Rittner, H. Schweizer 4. Physikalisches Institut, Universität Stuttgart, Stuttgart, GERMANY.

The short-time electron cyclotron resonance (ECR) excited nitrogen plasma treatments of unintentionally doped n-type GaN substrates were performed in order to investigate the effect of these treatments on GaN surfaces and to explore a possibility of a robust surface passivation of GaN. Measurements on reverse breakdown voltage and reverse saturation current of GaN Schottky diodes revealed a leaky surface produced by ECR excited nitrogen plasma treatment. Under nitrogen plasma exposure, there was a reduction in diode reverse breakdown voltage and an increase in forward and reverse currents. The results are consistent with creation of a thin n-type conducting surface region after ion bombardment of the GaN surface. Nitrogen plasma passivation effect on Ar ion beam etched GaN samples were also examined. We adopted Taguchi orthogonal table design to optimize the ECR nitrogen plasma operating parameters with respect to VB and then used the results to determine the reverse breakdown voltage dependences on the parameters close to the optimum operating point. Rather consistent results were obtained by Taguchi and nomal experimental methods. It is clearly indicated that the radio frequency (RF) power play the most important role on the surface passivation of ion beam etched GaN. After nitrogen plasma treatment, the diode reverse breakdown voltage is drastically increased from 15V to 95V. The lowest leakage current can be achieved with 600W microwave power, 0.5 mTorr nitrogen pressure and 30W RF power for 3 minutes. With the aid of nitrogen plasma passivation, we can effectively improve the Schottky characteristics of ion beam etched GaN and almost restore the surface conditions to the original ones. The nitrogen plasma passivation technique is thus able to be applied to the mesa formation of gate-recessed AlGaN/GaN HEMT transistors.

T6.31
OHMIC CONTACT FORMATION MECHANISM OF Pd-BASED CONTACT TO P-GaN. Dae-Woo Kim, Joon Cheol Bae, Woo Jin Kim, Hong Koo Baik, Dept of Metallurgical Engineering, Yonsei University, Seoul, KOREA; Chong Cook Kim, Jung Ho Je, Dept of Materials Science and Engineering, Pohang University of Science and Engineering, Pohang, KOREA; Chang Hee Hong, Dept of Semiconductor Science and Technology, Semiconductor Physics Center, Chonbuk National University, Chonju, KOREA.

III-V nitrides are promising materials not only for optical devices in the blue region of visible spectrum, but also for high speed electronic power devices. A problem to overcome in achieving high performance of GaN-based devices is the realization of good reliable ohmic contact. Up to the present, Ti/Al systems have been widely used as n-type ohmic contact and Ni/Au system for p-type. Although Ti/Al based contacts have the lowest contact resistance, these show the poor surface morphology and poor thermal stability. On the other hand, there have been few studies on the p-type ohmic contact and especially on the ohmic contact formation mechanism. In this study, we have investigated the ohmic contact formation mechanism of as-deposited Pd based ohmic contacts to Mg-doped p-GaN grown by metal organic chemical vapor deposition. In order to examine the room temperature ohmic behavior, various metal contact systems were deposited and I-V measurements were carried out. The ohmic behavior was obtained reliably only in Pd-based ohmic contact among the various metal contact systems. According to the results of synchrotron X-ray radiation, Pd (111) metal grew epitaxially on GaN (0001) surfaces with Pd[$1\bar{1}0$]//GaN[$11\bar{2}0$]. The closed-packed atomic planes of the Pd film were quite well ordered in surface normal direction as well as in the in-plane direction. On the other hand, other metals such as Au, Ti, Co, Cr, Ni, which has the very poor in-plane epitaxial quality, showed the poor current-voltage characteristics. Our electrical and microstructural study revealed that the room temperature ohmic characteristic of Pd based ohmic contact was related strongly to the in-plane epitaxial quality of metal on p-GaN.

T6.32
INVESTIGATION OF SURFACE CLEANING PROCEDURES AND CHARACTERIZATION OF NOVEL CONTACT PROCESSING FOR P-GaN. Noah S. Clay, Solid State Scientific Corporation, Hanscom Air Force Base, Bedford, MA; Helen M. Dauplaise, Kenneth Vaccaro, AFRL/Sensors Directorate, Hanscom Air Force Base, Bedford, MA; Leonid Krasnobaev, Implant Sciences Corporation, Wakefield, MA.

The p-GaN surface has been under close scrutiny because the electrical properties of the contact have been found to be relatively independent of the contact metal. To analyze the effects of the native oxide and adsorbed species on specific contact resistivity, a series of chemical, thermal, and low energy ion beam surface treatments were performed. Prior to each metal deposition, the surface was treated by one of the following processes: a) organic solvents, b) HF, c) aqua regia, d) UV/ozone, e) ion bombardment, f) vacuum heating or combinations thereof. Following a surface treatment, the elemental concentration of gallium, nitrogen, carbon and oxygen were determined by XPS analysis. Ni/Au, Pd/Au and Pt/Au contacts were deposited using e-beam evaporation. The TLM method was used to measure specific contact resistivity as a function of annealing time and temperature. New procedures for lowering the specific contact resistivity for p-GaN will be presented along with results from similar experiments with n-GaN.

T6.33
CHANNELING IN AlGaN/GaN HETEROSTRUCTURES CREATED BY ION BEAM ETCHING. Oliver Breitschadel, Jyh Tsung Hsieh, Bertram Kuhn, Ferdinand Scholz, Heinz Schweizer, 4. Physikalisches Institut, Universitat Stuttgart, Stuttgart, GERMANY.

Transistors based on the AlGaN/GaN material system have attracted wide attention due to their superior performance in high power and high temperature applications. GaN-transistors improvement shall be obtained by recess etching which is, however, only possible by using a dry etching technique like ion beam etching (IBE) because of the chemical stability of group III-nitrides. The recess etching step can lead to a strong channeling and thus to a decreasing of the electron mobility in the transistor channel. With low pressure MOVPE about 2 μm unintentionally doped GaN was grown on (0001) sapphire substrate followed by a AlGaN layer with a thickness of about 36 nm. 12 samples were prepared with Hall contacts in Van der Pauw geometry. The samples were subsequently etched by IBE at different angles from 0 to 50 degree and were measured before etching and after etching with respect to mobility, sheet resistance and sheet electron concentration. The mobility after etching decreases dramatically at small angles and remains nearly the same for angles larger than 30 degree. We attribute this behaviour to the channeling of the ions through the 36 nm AlGaN-layer. Similar to the observation in electron mobility a strong increase in resistivity after etching was shown for small angles and vanished for angles larger than 40 degree. The sheet electron concentration decreases independently of the etching angle up to 204% after etching. A model of defect traps in the upper regions of the AlGaN layer which were generated during ion beam etching seems to be consistent with this phenomena. Furthermore, we also observed that an annealing step after etching can lead to an improvement of the electrical properties in the AlGaN/GaN heterostructures. To avoid the problem of degraded electrical characteristics induced by dry etching during recess formation of AlGaN/GaN HEMTs, a larger ion incident angle is thus strongly suggested.

T6.34
MICROSTRUCTURE AND THERMAL STABILITY OF TRANSITION METAL NITRIDES AND BORIDES ON GaN. Jacek Jasinski, Lawrence Berkeley National Laboratory, Materials Science Division, Berkeley, CA, Institute of Experimental Physics, Warsaw University, Warsaw, POLAND; E. Kaminska, A. Piotrowska, A. Barcz, Institute of Electron Technology, Warsaw, POLAND.

Transition metal nitrides and borides are excellent candidates for capping layers in the technology of GaN-based devices. They present an exceptional combination of properties like low resistivity, high melting point, hardness and resistance to corrosion. Such characteristics might be essential in preventing the decomposition of semiconductor during thermal processing steps such as post-implantation annealing or formation of ohmic contacts. Thin films of TiN, ZrN, and ZrB_2 were chosen for this study. TiN films were deposited by reactive RF magnetron sputtering from Ti target in Ar/N_2 atmosphere. Zr-based layers were prepared by RF sputtering, from ZrB_2 or ZrN targets. We have used GaN epilayers grown on sapphire. Heat treatments up to 1200°C were performed in a rapid thermal annealer, with the use of a GaN proximity cap, under flowing N_2. The effects of the surface condition and the processing parameters on the crystalline structure and composition of GaN/capping layer systems were evaluated using HREM methods, SIMS and SEM. As the mode of operation of a particular capping layer may critically depend upon its crystalline structure, special attention was paid to the recrystallization processes. We show that the microstructure and mechanical properties of capping films are highly dependent on the surface morphology of GaN. Films deposited on rough surface peeled immediately after sample coating, while films deposited on smooth surface exhibited excellent adhesion to the substrate. Both titanium and zirconium getter residual gases from the ambient during deposition, therefore the as-deposited caps are contaminated. We demonstrate that the presence of impurities affects the thermal stability of GaN/capping layer systems. We have developed a method to remove contamination from Zr- and Ti-based layers by moderate-temperature pretreatment, enabling thus the fabrication of high quality capping layers. The thermal stability can be further improved up to 1200°C by the use of multilayer coatings.

T6.35
THERMAL EXPANSION AND LATTICE PARAMETERS OF IMPORTANT SEMICONDUCTORS AND SUBSTRATES. Robert R. Reeber and Kai Wang, Dept of Materials Science & Engineering, North Carolina State University, Raleigh, NC.

Thermal expansion and lattice parameters are important thermophysical properties of materials. A knowledge of their temperature dependence is essential for optimizing device design and crystal growth conditions while minimizing the residual stresses. Available experimental results from our work and the literature will be reviewed in terms of a quantitative high temperature predictive model. Tables of thermal expansion and lattice parameters for AlN, GaN, SiC, MgO, Al_2O_3, ZnO, and GaAs will be provided.

T6.36
REACTIVE ION ETCHING OF CVD DIAMOND FILM IN PLASMAS BASED ON O_2, Ar AND CF_4. Patrick W. Leech, CSIRO Division of Manufacturing Science and Technology, Melbourne, AUSTRALIA; Geoffrey K. Reeves and Anthony S. Holland, RMIT, Dept. of Communication and Electronic Engineering, Melbourne, AUSTRALIA.

A major issue in the realisation of active devices in diamond has remained the ability to lithographically pattern the film by etching. While the reactive ion etching of diamond has been reported in several previous studies, these have been restricted in the range of etch conditions and gasses. The present paper has compared for the first time the reactive ion etching of CVD grown diamond in an extensive range of plasmas (O_2, CF_4/O_2, O_2/Ar and Ar) using a single etch system. The details of etch rate and surface morphology have been characterized as a function of the parameters of the RIE system and interpreted in terms of the mechanism of etching. The etch rate of the diamond film was measured as a function of rf power, the chamber pressure and range of gasses. We have also examined the effect on etch rate of varying the ratio of the O_2/Ar gasses. The etching of the diamond film in both the O_2 and CF_4/O_2 plasmas has been attributed to a process of ion-enhanced chemical etching. In these plasmas, the etch rates were moderately large (30-50 nm/min) and linearly dependent on square root of bias voltage, $V_b^{1/2}$ with a high value of the slope (etch rate versus $V_b^{1/2}$) constant. In comparison, the etching of diamond in the Ar and Ar (35 sccm)/O_2 (10 sccm) plasmas has shown characteristics of low etch rate, a very low value of slope constant and insensitivity to chamber pressure suggesting a regime of sputter etching. An increase in the concentration of O_2 in the O_2/Ar plasmas resulted in a proportional rise in the etch rate due to an increasing contribution from ion-enhanced chemical etching.

SESSION T7: PROCESSING OF III-NITRIDE MATERIALS

Chairs: Melanie W. Cole and Kenneth A. Jones
Thursday Morning, April 27, 2000
Golden Gate A2 (Marriott)

8:30 AM *T7.1
DEVICE PROCESSING FOR GaN HIGH POWER ELECTRONICS. S.J. Pearton, A.X. Cao, H. Cho, C. Monier, Dept. of MS&E, Univ of Florida, Gainesville, FL; F. Ren, G. Dang, A.P. Zhang, Dept Chemical Engineering, Univ of Florida, Gainesville, FL; R.J. Shul, A.G. Baca, J. Han, Sandia National Laboratories, Albuquerque, NM; J.I. Chyi, Dept. Electrical Engineering, National Central Univ, Chung-Li, TAIWAN; J.M. Van Hove, SVT Associates, Eden Prairie, MN.

A variety of different GaN electronic devices are needed for applications in power microwave and high voltage/current switching, including HBTs, BJTs, Schottky and p-i-n rectifiers, MOSFETs and thyristors. We will discuss the ohmic and Schottky contact requirements, dry/wet etching, annealing and implant doping/isolation processes for these devices and give examples of the effect of the proceesing conditions on device performance.

9:00 AM *T7.2
CONTACTS TO AlGaN. Suzanne Mohney, Eric Readinger, The Pennsylvania State University, Dept of Materials Science and Engineering, University Park, PA.

Contacts to AlGaN are needed for a wide variety of nitride semiconductor devices currently under development. We have previously used thermodynamic calculations and experimental studies to investigate the metallurgy of contacts to GaN, and these studies helped us both design thermally stable contacts and better understand the interfacial reactions that occur in annealed or aged contacts. Here we discuss the similarities and differences we expect in the metallurgy of contacts to AlGaN compared to contacts to GaN, again considering the phase equilibria in these multicomponent systems. We then describe our recent work on the development of ohmic contacts to n-type AlGaN. For Al/Ti/n-AlGaN, we have found a strong influence of the ratio of Ti to Al on both the ultimate contact resistivity and the morphology of the contacts. Using compositions more rich in Ti than have generally been used on n-GaN, we have achieved contact resistivities of 10^{-5} Ω cm^2 on $Al_{0.31}Ga_{0.69}N$ with a carrier concentration of 2×10^{18} cm^{-3}. Other contact formation schemes to n-type AlGaN are also under investigation and will be described in this presentation.

9:30 AM T7.3
TECHNOLOGY DEVELOPMENT FOR OHMIC CONTACT TO P-GaN. D. Qiao, L.S. Yu, P.M. Asbeck and S.S. Lau, ECE Dept, University of California at San Diego, La Jolla, CA; J.Y. Lin and H. X. Jiang, Dept of Physics, Kansas State University, Manhattan, KS; A. Michel and R. Davis, North Carolina State University, Raleigh, NC.

Ohmic contact to p-type GaN with low contact resistance is essential for GaN heterojunction bipolar transistors, light emitting diodes, lasers, UV detectors and modulators. In this work, the influence of surface treatment, preannealing and metallization schemes on the fabrication of ohmic contacts to p-GaN was investigated. We explored various surface treatments, including HF, HCl; aqua regia; and KOH, to reduce the oxide on the sample surface and to alter the surface properties. It was found that surface treatment using boiling KOH or boiling aqua regia was more effective to improve the linearity of the contact characteristics (but not necessarily to increase the magnitude of the current at a given voltage). Preannealing of the samples is commonly used to improve the activation of Mg atoms as a p-type dopant. We studied the influence of the preannealing of the samples in forming gas and in N_2. It was found that preannealing in N_2 at high temperature for an extended period (e.g. longer than 20 minutes at high temperatures) was detrimental to the contacts. Preannealing in forming gas followed by annealing in N_2 or in vacuum yielded the best ohmic behavior. Various metal systems were also studied to achieve low barrier heights and optimal semiconductor/metal interactions. We found that a single Ni layer contact improves the reactions between metal and the underneath p-GaN layer, compared to the commonly used Au/Ni contact. The Ni GaN interactions may induce the outdiffusion of Ga to form Ga vacancies near the surface regions of the sample. Ga vacancies are believed to cause p-type doping in GaN. The Au(800Å)/Ni(300Å)/Pt(200Å)/GaN metallization was also found to be a viable contact on p-GaN. An optimized process of forming ohmic contacts to p-type GaN, including the surface treatment, preannealing and metallization, will be reported in this presentation.

9:45 AM T7.4
ELECTRIC AND MORPHOLOGY STUDIES OF OHMIC CONTACTS ON AlGaN/GaN HETEROSTRUCTURES. Vinayak Tilak, Roman Dimitrov, Michael Murphy, Joe Smart, William Schaff, James Shealy, Lester Eastman.

AlGaN/GaN is a promising system for high power electron devices. Quality of ohmic contacts is a critical parameter in determining the performance of the device, as low source resistance is needed for good g_m values. Although we have achieved a transfer resistances of 0.35 Ω mm and ρ_c of 9.5e-7 Ω cm^{-2} the morphology and edge acuity of these contacts are poor. Edge acuity is critical for reducing the source-drain spacing without shorting the device and also in improving the breakdown voltage of the device. Poor morphology may increase the noise of these devices in low noise applications. The standard ohmic contact recipes consists of a combination Titanium and Aluminum with Nickel and/or Gold on top. This is annealed at 800°C-950°C. In this work we study the ohmic contacts on unintentionally doped $Al_{0.3-0.5}$ GaN/GaN heterostructures. We look at different ratios of Ti/Al from 0 to 2 to determine which is the best ratio to use in terms of morphology and in terms of electrical characteristics. From our studies we see that the morphology is bad until a Ti/Al ratio of 0.25. For all ratios greater than 0.25 the contacts have good morphology. Also, we discuss the role of gold in both the surface morphology and the electrical characteristics of the contacts. We will also discuss the impact on morphology and electrical characteristics the addition of a refractory metal to the Ti/Al system.

10:30 AM T7.5
INDUCTIVELY COUPLED HIGH-DENSITY PLASMA-INDUCED ETCH DAMAGE OF GaN MESFET's. R.J. Shul, L. Zhang, A.G. Baca, C.G. Willison and J. Han, Sandia National Laboratories, Albuquerque, NM; S.J. Pearton and F. Ren, University of Florida, Gainesville, FL.

The fabrication of a wide variety of GaN-based photonic and electronic devices depends on dry etching. The majority of dry etching processes rely on ion-assisted removal of the substrate material. Under conditions of both high plasma flux and energetic ion bombardment, GaN etch rates greater than 500 nm/min and anisotropic etch profiles are readily achieved in Inductively Coupled Plasma (ICP) etch systems. Unfortunately, under these conditions plasma-induced damage often occurs. Attempts to minimize such damage by reducing the ion energy or increasing the chemical activity in the plasma often result in a loss of etch rate or anisotropy which significantly limits critical dimensions and reduces the utility of the process for device applications requiring vertical etch profiles. It is therefore necessary to develop plasma etch processes which couple anisotropy for critical dimension and sidewall profile control and high etch rates with low-damage for optimum device performance. We have recently reported large gate leakage currents for GaN JFETs patterned using an ICP etch system. High leakage currents may have been due to the plasma-induced damage to the p-n junction. Plasma-induced damage has been reported to be strongly dependent upon ion energy and plasma density. Recent results for etch-induced damage on the electrical performance of GaN p-n diodes and sheet resistance of n- and p-type GaN are summarized. In addition device performance of GaN MESFETs exposed to an ICP-generated Ar plasma will be presented. The effect of ion energies and plasma densities on the gate leakage current, transconductance, and source and drain series resistance will be reported.
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-ACO4-94AL85000.

10:45 AM T7.6
ETCH DAMAGE ASSOCIATED WITH ION CHANNELING IN GaN. Elaine D. Haberer*, Ching-Hui Chen**, Amber Abare**, Monica Hansen*, Steve Denbaars*, Larry Coldren**, Umesh Mishra**, Evelyn L. Hu**. *Materials Dept, University of California,

Santa Barbara, CA, **Dept of Elec. and Comp. Engr., University of California, Santa Barbara, CA.

GaN is known to be a highly chemically inert, thermally stable material. Because it is resistant to most conventional wet etchants, dry etch processes are critical in the development of GaN device technologies. Unfortunately, dry etch processes can also cause extensive lattice damage which can significantly degrade device performance. In order to minimize etch damage, it is important to understand the dominant damage mechanisms in GaN. Our experiments employ InGaN quantum wells (QWs) as sensitive probes of the sub-surface distribution of ion-induced damage. The QWs were situated 1000 ≈ below the substrate surface. The samples were bombarded with Ar+ ions at various ion energies, beam currents and times. Room temperature PL measurements were taken before and after bombardment using a He-Cd laser as an excitation source. The amount of damage was quantified by comparing the maximum PL intensity before and after etch. The relative PL degradation of the InGaN quantum wells appeared to much greater than is true for GaAs QWs subject to the same conditions. Subsequent angle-dependent ion bombardment studies showed the greatest decrease in luminescence for InGaN/GaN samples bombarded by ions at normal incidence, along the [0001] direction. The greatest decrease for GaAs QW samples occurred at 45°C incidence, along the <011> direction. We believe that the data show evidence of the importance of channeling in the deep propagation of ion damage: normal incidence bombardment of the InGaN/GaN is along the preferred channeling direction, leading to deep penetration of ion damage. Changes in damage with increased bombardment time, and the possible diffusion of defects will also be explored.

11:00 AM T7.7
BACKSIDE-ILLUMINATED PHOTOELECTROCHEMICAL WET ETCHING OF GALLIUM NITRIDE STRUCTURES. A.R. Stonas[1], T. Margalith[2], E.V. Etzkorn[2], P. Kozodoy[1], S.P. DenBaars[1,2], D.R. Clarke[2], L.A. Coldren[1,2], U.K. Mishra[1], E.L. Hu[1,2]. [1]UCSB, Electrical and Computer Engineering Dept., [2]UCSB, Materials Dept., Santa Barbara, CA.

Photoelectrochemical (PEC) wet etching is a technique that has had extensive application in the patterning of the chemically inert GaN-based materials. The technique has demonstrated the capability of carrying out dopant-selective and bandgap-selective etching, achieving vertical etch rates of several thousand angstroms per minute. The presence of a higher bandgap sapphire substrate for many GaN structures allows the possibility of carrying out PEC etching by illumination of the material through the sapphire substrate (backside etching), rather than by direct illumination of the GaN material itself (frontside). The resulting backside etch characteristics are dramatically different from frontside etching: deeply undercut structures such as cantilievers can be formed, with lateral etch rates as high as 5 μm/minute. Etching of the material on the side farthest removed from the light source is also observed, where the etch generally decorates defects in the material. We will discuss the differences in mechanisms of frontside and backside etching, as determined using a KOH-based (11% w/w) solution. We will also examine the selectivities and etch profiles of various MOCVD-grown InGaN/GaN heterostructures, and discuss the extremely deep etching ($\sim$20μm) of HVPE-grown GaN. Samples etched ranged in thickness from a few microns thick (MOCVD-grown) to over 30 microns (HVPE-grown). All selectivity studies were performed on MOCVD-grown material, with structures ranging in complexity from simple p-n junctions to BJTs and laser structures.

11:15 AM T7.8
FLICKER NOISE CHARACTERISTICS OF PLASMA-INDUCED DAMAGED GaN PLANAR RESISTORS. H.W. Choi, S.J. Chua, Centre for Optoelectronics, Department of Electrical Engineering, National University of Singapore, Singapore, SINGAPORE; A. Raman, Institute of Materials Research & Engineering.

We attempt to investigate the low-frequency (LF) noise performance of GaN planar resistors which were subjected to inductively-coupled plasma (ICP) etching damage. Experiments were performed on MOCVD grown n-type GaN samples of 2μm thickness and doped to approximately 10^{17} cm^{-3}. Planar resistors of Hallbar structures were fabricated by photolithography patterning followed by ICP etching. Ti/Al ohmic contacts were deposited using the electron beam evaporation technique. The resistors were subsequently subjected to plasma-induced damage through ICP etching. Current noise spectral density was measured following the four-point probe measurement scheme on the damaged sample and an untreated sample from the same wafer. Almost an order of magnitude reduction of noise spectral density was observed from the damaged sample compared to the untreated sample. LF noise is well known to be associated with the quality of the material, yet it is unlikely that the etching process would contribute to reduction of defects. In fact dislocations were observed on SEM microphotograph for the damaged sample. A 60% reduction of PL intensity was also detected by photoluminescence measurements. These results rule out such a possibility. It is deduced that the noise reduction is due to the formation of a lower resistance ohmic contact with the plasma-induced damaged surface. The rough and abraded surface created from the etching process favours the formation of low resistance ohmic contacts, consistent with contact resistance measurements. We believe that the mechanism involves the incorporation of impurities onto the surface of GaN, giving rise to a nonradiative recombination level which increases the surface recombination velocity. XPS measurements identified traces of Cl (the plasma chemistry being Cl_2 and BCl_3), together with a marked increase in O content on the surface of the treated sample. The role of ICP etching is to expose more dangling bonds, thus increasing the affinity of the surface to oxygen.

11:30 AM T7.9
SURFACE DISORDERING AND NITROGEN LOSS IN GaN UNDER ION BOMBARDMENT. S.O. Kucheyev, H.H. Tan, C. Jagadish, J.S. Williams, Department of Electronic Materials Engineering, The Australian National University, Canberra, AUSTRALIA; M. Toth, M.R. Phillips, Faculty of Science, University of Technology, Sydney, AUSTRALIA; G. Li, Ledex Corporation, Kaohsiung, TAIWAN; S.J. Pearton, Department of Materials Science and Engineering, University of Florida, Gainesville, FL.

Even during bombardment at liquid nitrogen temperatures, GaN is quite resistant to ion disordering due to efficient defect annihilation processes. However, defect annihilation is not perfect and residual disorder accumulates as a function of increasing ion dose, often with preferential disordering at the surface[1]. In this study, c-axis GaN films grown on sapphire substrates have been bombarded with H, C and Au ions at various temperatures. Irradiated and annealed samples have been studied by Rutherford backscattering and channeling, atomic force microscopy, cathodoluminescence depth and kinetic profiling and backscattered or secondary electron imaging. Results indicate enhanced surface disordering of GaN and preferential loss of N as the ion dose increases. This surface disordering and dissociation process under ion bombardment does not appear to be very sensitive to implantation temperatures up to a few hundred degrees Centigrade. Capping of GaN with SiO_2 and Si_3N_4 layers prior to ion bombardment does not eliminate surface disordering and N loss. Indeed, for Au ion doses which exceed the amorphous threshold, Ga droplets have been observed on the surface after ion bombardment and annealing. Such preferential loss of N may explain why high dose ion damage cannot be completely removed by thermal annealing. In addition, this study may have significant implications for residual disorder and N-deficient GaN surfaces following reactive ion etching, particularly in light of the recently reported p-to n-surface conversion for etched GaN[2].

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11:45 AM T7.10
DIODE FABRICATION WITH HIGH DOSE Mg^+ ION IMPLANTATION INTO n-GaN. Leonid Krasnobaev, Agajan Suvkhanov, Implant Sciences, Wakefield, MA; Lionel Bouthillette, Kenneth Vaccaro, Sensors Directorate, FRL, Hanscom AFB, Bedford, MA; Noah Clay, Solid State Scientific Corporation, Hollis, NH; Brendan Gaffey, Yale University, Dept of Electrical Engineering, New Haven, CT.

GaN doping by ion implantation at elevated temperatures has definite advantages over ion implantation at room temperature. The elemental defects, vacancies, and interstitials produced by ion irradiation are more mobile at elevated temperatures, and annihilate more effectively in interaction with each other, with dislocations, and with crystal grain boundaries. The impurity solid solubility in GaN increases as the temperature rises. N-type GaN, grown on Al_2O_3 or SiC with a conductive buffer layer, was implanted by Mg^+ ions with doses of $5x10^{15}$- $5x10^{16}$ cm^{-2} at implant temperatures of 800-1000°C. All implants were done through AlN or metal capping films. Before and after implantation, and after annealing at 1100-1300°C, the structures were analyzed by RBS, photoluminescence, and Hall effect measurements. The second ion implantation process was employed for device insulation. The properties of the diode structures are presented by I-V characteristics and LED wavelength spectrums vs. direct current through the p-n junction. The comparison of ion implanted planar diodes with vertical diode structures grown by MOCVD is presented and discussed.

SESSION T8: SiC PROCESSING
Chairs: Stephen J. Pearton and James S. Williams
Thursday Afternoon, April 27, 2000
Golden Gate A2 (Marriott)

1:30 PM *T8.1
IMPLANT ACTIVATION IN SiC AND ITS EFFECT ON THE CONTACT RESISTANCE OF OHMIC CONTACTS TO IT. Kenneth A. Jones, Army Research Lab, Adelphi, MD.

Due to its exceptionally low diffusion coefficient, SiC is locally doped by ion implantation. The implants have to be activated at temperatures at which possibly some of the dopants and silicon preferentially evaporate. This causes the SiC surface to roughen and the electrical properties to change due to the loss of dopants and possibly the formation of point defects such as silicon vacancies. AlN caps can prevent these problems up to annealing temperatures of ~1600°C at which point, it, too, begins to evaporate. Graphite caps do not work as well both because the implant activation is lower and it crystallizes at temperatures > 1650°C and can only be removed by ion beam milling. However, when used in conjunction with the AlN as an AlN cap, this double layer can be used successfully as a cap up to 1700°C. Above this temperature the vapor pressure of the underlying N2 blows holes in the graphite cap. However, both the p- and n-implants can essentially be completely activated by the 1700°C anneal. We make traditional Ni and Ti/Al ohmic contacts to n- and p-type SiC with various stages of implant activation and attempt to interpret the state of activation with the contact resistance as determined by TLM measurements.

2:00 PM *T8.2
THE MATERIALS PROPERTIES OF A NICKEL BASED COMPOSITE OHMIC CONTACT To n-SiC FOR PULSED HIGH POWER SWITCHING APPLICATIONS. M.W. Cole, P.C. Joshi, C. Hubbard, M. Wood, D. Demaree and M. Ervin, US Army Research Laboratory, Weapons and Materials Research Directorate, Aberdeen Proving Ground, MD; F. Ren, Univ. of Florida, Dept. of Chemical Engineering, Gainesville, FL.

SiC has great promise as a material for high power and high temperature device applications. One of the key technology areas which must be addressed before SiC can realize its great potential is the issue of device quality ohmic contacts. Due to its reproducible low specific contact resistance, $< 5x10^{-6}$ ohm-cm^2, Ni has been deemed the industry standard metallization for ohmic contacts to n-SiC. However, the anneal cycle required to achieve this low specific contact resistance results in a broad, heavily voided, irregular metal-SiC interface and extremely rough surface morphology. Additionally, thermal fatigue testing, mimicking the in service pulsed high power switching operational stress regime, causes severe degradation of the Ni-SiC mechanical properties. In order to retain the low specific contact resistance and suppress the undesirable metal-semiconductor interfacial characteristics of Ni ohmic contacts we have developed a Ni based composite ohmic contact to n-SiC, Ni/WSi/Ti/Pt. The material properties of the as-deposited and annealed Ni/WSi/Ti/Pt composite contact metallization to 4H n-SiC were quantitatively assessed via AFM, FESEM, AES, RBS, TEM and wafer stress measurements. Additionally, the reliability of this composite ohmic contact metallization in response to palpitated high power switching, i.e., the in service device operational environment, was assessed via acute pulsed thermal fatigue testing. Our results demonstrated that ohmic contact formation was achieved via RTA for 30 sec at temperatures ranging from 900 to 1000°C. The post-annealed surface morphologies were smooth and contact-SiC interface appeared uniform and abrupt. The electrical, compositional and structural integrity of the contact-SiC interface suffered minimal degradation after exposure to pulsed thermal fatigue testing. Details of the aspects of contact formation and the results of the palpitated thermal fatigue testing will be presented and discussed.

2:30 PM T8.3
STABLE Ti/$TaSi_2$/Pt OHMIC CONTACT ON N-TYPE 6H-SiC EPILAYER AT 600°C. Robert S. Okojie, NASA Glenn Research Center, Instrumentation and Controls Division, Cleveland, OH.

Most existing wide-bandgap devices are limited to temperatures lower than 400°C, primarily due to the degradation of the contact metallization. Finding the appropriate metallization schemes required to support long-term device operation at high temperatures up to 600°C have remained a major challenge [1-3]. Prominent among the failure mechanisms are instability of contact resistance, premature contact rectification, runaway diffusion barriers, and adhesion. This paper will present results of the electrical characteristics of in vacuo sequentially deposited Ti/$TaSi_2$/Pt contact metallization on n-type 6H-SiC epilayer tested in atmosphere at 600°C. This work is in response to reliability issues associated with high temperature ohmic contact metallization. Thermodynamic and thermochemical analysis are used as basis for developing a broader understanding of the relevant factors that fundamentally influence stable contact resistivity on SiC devices during long haul operation at elevated temperatures. Contact resistivity in the range of factors of 10^{-6} to $10^{-4}\Omega\cdot cm^2$ is obtained and remains relatively stable for over thirty hours. No evidence of buckling or peeling is observed, thus preserving the mechanical and the electrical integrity of the scheme. Auger electron spectroscopy (AES) performed after five and ten hours of thermal treatment at 600°C in atmosphere indicates no dramatic changes at the interfacial reaction zones. The intrusion of oxygen from the environment is observed to be successfully arrested few angstroms into the top platinum layer, thus preventing further inward diffusion toward the contact surface. The success of this scheme is attributed to the diffusion barrier characteristics of $TaSi_2$. The result confirms Ti/$TaSi_2$/Pt as a viable metallization scheme for device operation up to 600°C, thereby opening new opportunities for the successful implementation of high temperature devices with improved reliability. It also demonstrates a less complex process methodology of a three-layer metal stack that is compatible with conventional fabrication process.
This work was funded by Ford Microelectronics, Inc., Colorado Springs, CO.
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3:15 PM T8.4
HIGH DOSE TITANIUM ION IMPLANTATION INTO EPITAXIAL Si/3C-SiC/Si LAYER SYSTEMS FOR ELECTRICAL CONTACT FORMATION. Jörg K.N. Lindner, Stephanie Wenzel and Bernd Stritzker, Universität Augsburg, Institut für Physik, Augsburg, GERMANY.

The formation of reliable, high-temperature stable Ohmic and Schottky contacts on SiC is one of the challenging technological problems which remains to be solved before the superior high-temperature properties of the wide-band semiconductor SiC can be exploited in microelectronic devices. Both, transition metal silicides and transition metal carbides have been suggested as possible candidates for this purpose. Among the large number of transition metal atomic species, titanium is particularly promissing, as it forms both, a highly conductive disilicide which is readily being used in Si VLSI technology, and a metal carbide, which may grow epitaxially on 3C-SiC, as it has the same crystal symmetry and a lattice mismatch of only 0.7% at room temperature. We have previously shown that high-dose implantation of Ti ions into 3C-SiC leads to the formation of ternary $Ti_xSi_{1-x}C$ compound layers of graded composition. Moreover it is known that high-dose Ti implantation into Si can be applied to synthesize homogeneous near-surface $TiSi_2$ layers in silicon. In the present study, the conversion of the Si top layer of an epitaxial Si/3C-SiC/Si layer system formed by ion beam synthesis into a titanium silicide layer by high-dose titanium implantation is described. For this purpose, buried epitaxial 3C-SiC layers were fabricated by 180 keV high-dose carbon implantation into Si(100) and Si(111) at 450°C and subsequent annealing at 1250°C. The resulting Si/SiC/Si layer systems were subsequently implanted with 180 keV Ti^+ ions at various temperatures and doses in the low 10^{17} Ti/cm^2 range. The structure and composition of the metal/SiC/Si layer systems formed is characterized in the as-implanted state and after annealing at temperatures up to 1000°C using RBS, channeling, XRD, and cross-sectional TEM.

3:30 PM T8.5
EXPERIMENTAL INVESTIGATION OF Ge IMPLANTED SiC SUBSTRATES. Gary Katulka*, James Kolodzey, Kris Roe, Mike Dashiell, Thomas Adam, Department of Electrical and Computer Engineering, University of Delaware, Newark, DE; Robert G. Wilson, Stevenson Ranch, CA; Mei Wei Tsao and John Rabolt, Department of Material Science and Engineering, University of Delaware, Newark, DE; Charles Swann, Bartol Research Institute, University of Delaware, Newark, DE. *U.S. Army Research Laboratory, Aberdeen Proving Ground, MD.

SiC substrates alloyed with Ge have been investigated experimentally as candidate materials for SiC/SiCGe heterostructure semiconductor devices. SiC substrates implanted with Ge atoms have been investigated previously through X-ray diffraction (XRD), Rutherford backscattering spectroscopy (RBS), Raman spectroscopy and electrical measurement techniques. The resulting data show implanted layers of SiC:Ge are thermally stable to as much as 1000 C. X-ray data show an increase in the lattice constant that implies the Ge is substitutional. The lattice constant agrees with the composition obtained by RBS measurements, assuming Vegards linear law. Our current research is focused on the affects of ion implantation as well as the processing conditions on the optical and electrical properties of SiC:Ge alloys. The Ge implantation is carried out with an ion beam energy of between 200 - 300 keV with different doses into SiC substrates having various conductivity types. Additionally, experimental results are obtained for SiC:Ge alloys processed by thermal annealing over an extended temperature range. We will report on the affect of Ge on the optical transmission, Raman spectra, and the electrical conductivity.

3:45 PM T8.6
CHARACTERIZATION OF n-TYPE LAYER BY S^2 ION IMPLANTED IN 4H-SiC. Yasunori Tanaka[1,2], Naoto Kobayashi[1,2], Hajime Okumura[1,2], Sadafumi Yoshida[1,2], Masataka Hasegawa[1], Masahiko Ogura[1], Hisao Tanoue[1] and Kazuo Arai[1,2]. [1]Electrotechnical Laboratory, Tsukuba, Ibaraki, JAPAN, [2]Ultra-Low-Loss Power Device Technology Research Body, Tsukuba, Ibaraki, JAPAN.

For n-type dopant in silicon carbide, we usually use nitrogen or phosphorus for device application because of their relative shallow impurity levels. In this paper we will present sulfur doping for a new n-type dopant by ion implantation in 4H-SiC. In this study we used 4H-SiC(0001) wafers with epi-layer(p-type, p$\sim$1.0X10^{16}/cm^3, Si-face,10μm) purchased from Cree Research Inc. To make up the S-implanted layer as box profile we carried out the multiple energy implantation in the energy range of 40-400keV with the total dose of 5.0X10^{14}-5.0X10^{15}/cm^2 at 500°C. The implanted samples were annealed in the furnace at 1600°C for 20 minutes in Ar ambient for the electrical activation of dopants. Hall effect measurements were carried out to investigate the electrical property. For 5.0X10^{14}/cm^2 dose we estimated the impurity level from conduction band at $\sim$150meV. This value is relative deeper than that of nitrogen. For more higher dose, 1.0X10^{15}/cm^2, we estimated it at $\sim$120meV.

4:00 PM T8.7
THE EFFECTS OF POST-GROWTH ANNEAL CONDITIONS ON INTERFACE STATE DENSITY NEAR THE CONDUCTION BAND EDGE AND INVERSION CHANNEL MOBILITY FOR SiC MOSFETs. G.Y. Chung, C.C. Tin, J.H. Won and J.R. Williams, Physics Department, Auburn University, AL; K. McDonald[1], K. McDonald, R.A. Weller[1,2], M. Di Ventra[1], S.T. Pantelides[1] and L.C. Feldman[1]. [1]Department of Physics and Astronomy, [2]Department of Computer Science and Electrical Engineering, Vanderbilt University, Nashville, TN.

Silicon carbide is a promising semiconductor for high-power, high-temperature, and high frequency devices because of superior material properties such as wide bandgap, high breakdown field, high carrier saturation drift velocity, and high thermal conductivity. One of the most important advantages of SiC compared to other wide bandgap semiconductors (the group III nitrides and diamond) is that SiC can be oxidized to form a high-quality SiO2 dielectric layer. Silicon carbide n-channel inversion MOSFETs have been demonstrated for both the 4H and 6H-SiC polytypes; however, inversion channel mobility is noticeably lower for 4H-SiC compared to 6H. This is an unexpected result since 4H-SiC has a higher bulk carrier mobility. Many researchers have characterized the interface trap density (Dit) between mid-gap and the valence band edge (E-Ev = 0.5-1.5eV) using p-SiC MOS capacitors and have optimized oxidation conditions and various post-growth anneal conditions to decrease Dit over this energy range. However, it is the interface trap density near the conduction band that affects channel mobility for n-channel inversion MOSFETs. This interface state density can be studied using standard C-V techniques applied to oxidized n-epitaxial layers. We will report room temperature C-V results for n-type 4H and 6H-SiC that show that the interface state density near the conduction band edge is higher for the 4H polytype, and that the interface state density is a function of the Si / C ratio used to control the nitrogen doping concentration during grow of the 4H and 6H epilayers. We will also report results for post-oxidation anneals in NO, and post-metallization anneals in hydrogen carried out in an effort to passivate interface states near the conduction band edge. Ab initio theoretical calculations allow us to propose a mechanism of how N and H passivate defect states in the upper part of the SiC band gap introduced by C atoms and clusters at the interface. Lateral n-channel MOSFETs are being fabricated using an optimized post-growth annealing process, and the results of channel mobility measurements for these devices will be reported. This work was supported by DARPA Contract MDA972 98-1-0007 and EPRI Contract W0806905. Program managers D. Radack (DARPA), J.C. Melcher (EPRI). Program technical monitors J. Zolper (ONR), F.R. Goodman (EPRI).

4:15 PM T8.8
EFFECTS OF ELECTRODE SPACING ON REACTIVE ION ETCHING OF 4H-SiC. J. Bonds, G.E. Carter, J.B. Casady, Mississippi State Univ, Emerging Materials Research Laboratory, Electrical & Computer Engineering Department, Starkville, MS; J.D. Scofield, U.S.A.F. Research Laboratory, Wright-Patterson AFB, OH.

4H-SiC is the most mature of wide bandgap semiconductors, with applications in numerous high-power and high-frequency areas now being exploited commercially. Because of its chemical inertness, the only practical etch process for deep via holes in monolithic microwave integrated circuits (MMIC's) and microelectromechanical systems (MEMS) is through the use of dry (or plasma) etching [1]. Of the dry etching techniques, reactive ion etching (RIE) is the lowest-cost technique for batch, high-throughput, high-yield processing. Here, we examine the effect of varying the electrode-to-anode spacing to maximize the 4H-SiC etch rate using RIE.
Electrode space variation in a 13.56 MHz RIE system resulted in dramatic etch rate differences of 4H-SiC. Previous work, specifically SF_6 with the fraction being at or below 50%, has shown the best etch rates at pressures of 100 to 350 mTorr [2]. Another study done on 4H-SiC surface roughness due to reactive ion etch using SF_6 and O_2 showed that the surface roughness was not significantly improved, but not adversely affected by the same combination [3]. A one-hour etch performed at a power of 10 W (0.906 W/cm^2) and pressure of 150 mTorr resulted in an etch rate of 267 Å /min., which is typical of our baseline RIE process at an electrode-to-sample spacing of 2.540 cm. The anisotropic etch resulting from these conditions had good surface morphology, but is impractical for deep etches at this relatively slow rate. The investigation into the effects of electrode spacing on the etch rate allow one to further optimize the etch rate without resorting to excessive power density. Measurements were taken at electrode spacings of 2.540 cm, 1.905 cm, and 1.270 cm. A peak etch rate of 2205 Å /min. was achieved under these conditions, which is one of the highest reported RIE rates for 4H-SiC. Surface morphology, mask selectivity, and other issues are reported in the full manuscript.
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4:30 PM T8.9
DEEP RIE PROCESS FOR SILICON CARBIDE POWER ELECTRONICS AND MEMS. Glenn Beheim, NASA Glenn Research Center, Cleveland, OH.

Reactive ion etching of Silicon Carbide to depths ranging from tens of micrometers to 100 micrometers or greater is required for the fabrication of vertical structure Silicon Carbide power electronics and Silicon Carbide MEMS. The low reactivity of Silicon Carbide, however, makes it difficult to obtain such deep etching at reasonable rates and with adequate selectivity with respect to the etch mask. A high rate, anisotropic etch process for Silicon Carbide has been developed using an Inductively Coupled Plasma (ICP) etch system and a fluorine-based etch chemistry. The ICP enables a high plasma density and a high density of reactive species at low pressure (approximately 5 mTorr), which provides for high rate anisotropic etching (0.3 micrometers/min and greater) and residue-free etched surfaces. An etch selectivity of 60:1 with respect to an ITO mask allows etch depths of 100 micrometers or more. The effects of process parameters on etch rate, selectivity, and the quality of etched surfaces will be presented.

4:45 PM T8.10
SILICON CARBIDE DIE ATTACH SCHEME FOR 500°C OPERATION. Liang-Yu Chen*, Gary W. Hunter and Philip G. Neudeck, *AYT/NASA Glenn Research Center, Cleveland, OH.

High temperature electronics and sensors are needed for harsh environment space and aeronautical applications such as inner solar system exploration or aeronautical engine monitoring and control (electronics/sensors located in an aeronautical engine environment). Single crystal silicon carbide (SiC) has such excellent physical, chemical, and electronic properties that SiC based semiconductor electronics can operate at temperatures in excess of 600 degree C well beyond the high temperature limit for Si based semiconductor devices. SiC semiconductor devices have recently been demonstrated to be operable at temperatures as high as 600 degree C, but only in probe-station environment partially because suitable packaging technology for the devices at high temperature (500°C and beyond) does not exist. One of the core technologies for high temperature electronic packaging is low electrical resistance semiconductor die-attach. This paper discusses a conductive die-attach scheme and results of test carried out at 500°C in air. A 1mm x 1mm SiC Shottky diode die is attached to aluminum nitride (AlN) ceramic substrate using precious metal based thick-film materials. The attached test die survived both electrically and mechanically a soak test at 500°C in oxygen containing air environment for more than 500 hours. The electrical resistance of the die-attach interface estimated by I-V curves of the attached diode during and after heat treatment at elevated temperatures indicated stable and low attach-resistance with annealing time (500 hours). The mechanical shear strength of die-attach structure as well as further durability testing will also be discussed.