SYMPOSIUM T
Wide-Bandgap Electronic Devices
April 24 – 27, 2000

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*Invited paper
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 applications is presented. Devices 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 switches 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 N00014-95-1-1309), DARPA (Contract MD9728-99-C-0011), and NSF Center for Power Electronics Systems (Award Number EEC-9721677).

2:00 PM **T1.2**
**ELECTRICAL BEHAVIOR OF X-RAY IMAGED CRYSTAL DEFECTS IN SiC HIGH FIELD DEVICES**
Philip G. Neudeck, Maria A. Kuczenski, NASA Glenn Research Center and Lewis Field, Cleveland, OH; Michael Dudley, William M. Vetter, Hubin B. Sta, 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 the electrical behavior of closed core screw dislocations in high-power switching devices, because these defects tend to be invisible in 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 foreseeable future. In silicon power electronics experience, undesired lateral nonuniformities in material properties across the high field area of a power device, e.g., nonuniformities caused by crystal dislocation defects and impurity charging, have historically led to reliability problems in demanding high-power systems, with higher voltage devices being most susceptible to failure. Similarly 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 electrical 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. Experimental 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 p+AlN/ Si OR SiC MIS HYDROGEN SENSOR**
Elhamin Serai, Wayne State Univ, Dept of Chemical Engineering, Detroit, MI; Gregor W. Asmer, Wayne State Univ, Dept of Electrical Engineering, Detroit, MI; K.Y. Simon Ng, Wayne State Univ, Dept of Chemical Engineering, Detroit, MI; Ranaa Naik, Wayne State Univ, Dept of Physics, Detroit, MI; Changhe Hong, Lajos Rami, Department of Electrical Engineering, Wayne State University, Detroit, MI.

An AlN (insulator) MIS Hydrogen Sensor was created using Plasma Source Molecular Beam Epitaxy (PSMDE) deposition on 6H-SiC and Si(111) substrates. The employment of AlN, instead of conventionally used SiO₂ or TiO₂, allows the device to operate at high temperatures as well as room temperature. A p⁺ 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 Pd and Pd⁺ thickness have been tested. 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 L-V measurements were performed for almost 100% efficiency from 1 kHz to 1 MHz. When Hydrogen was introduced in the testing chamber a shift in the C-V curve occurred. Similar results were obtained in L-V measurements, 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 Reaj, 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 team in Dayton has demonstrated excellent 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**
Gerard Wachtuk, Martin Lades, Winfried Kound, 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 an 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 series resistance 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 describes, on the continuous-field level, various physical effects particularly relevant to SiC devices. This includes, among others, several field-dependent generation-recombination mechanisms specific of widegap materials and their impact on the blocking capability, the consequences of microstrip material properties such as the carrier mobility, the carrier concentration, 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 new 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/AIN/n-TYPE 6H-SiC(0001) HETEROSTRUCTURES**
M.O. Atef, North Carolina State University, Raleigh, NC.

Aluminum nitride (AIN) is a wide bandgap semiconductor (6.2 eV) which is nearly perfect 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 (e₈₉ = 5.5) and a high breakdown field (~1.5 x 10⁶ V/cm). These properties make AlN an attractive candidate for the formation of nearly ideal heterointerface with 6H-SiC, which can be exploited in metal/AIN/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 wurzite 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 coherent. The carrier 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, which can be explained in terms of the shifts 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 $10^{11} \text{ cm}^{-2}$ 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 process. In addition, the linear fitting of the trap density is the trap density is comparable to those reported for deposited oxides on n-type 4H-SiC (0001), and indicates that the interface between AlN and Si terminate 4H-SiC is of a high quality suitable for device application.


4:30 PM TL7

IMPLANTED BIPOLAR TECHNOLOGY IN 4H-SiC. Nick Wright, Mark Johnson, Anthony O'Neill, Alton Horfall, Sylvie Ortolandi, Katsu 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 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 annealing on the electrical characteristics of the junctions will be presented. In addition, techniques for post-implant surface recovery using RIE etch coupled to oxidation/strip processing will be presented. Using such techniques, low-leakage transistors with high breakdown voltages have been grown and detailed electrical characterization up to 7000 V 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 utilizing 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 optimization.

4:45 PM TL8


4H-SiC is considered as a promising material for fabrication of high power microwave diodes (e.g. p-n and IMPATT diodes). This kind of diodes do not need large area mesa structures and may utilize commercial epitaxial wafers having relatively high defect and micro-impurity densities and incorporate devices with low breakdown voltages. 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 characterization of 4H-SiC pn diodes with extremely low differential resistance. A novel structure was formed on commercial 4H-SiC pn epitaxial wafer. Wafer was cut into chips, which were mounted in standard microwave diode packages. Diodes had zero bias capacitance of 2 to 5 pF depending on mesa structure diameter, series differential resistance $\sim 5 \Omega$ measured at forward bias and avalanche breakdown voltage of 370 V. They were capable to dissipate power density of 150 kW/cm² at CW avalanche current 16 mA, and 4.2 MW/cm² at pulse avalanche current 1.1 A. The electrical - LV characteristics of the diodes were measured at the front edge of the pulse. Diode structure parameters obtained from C-V, L-V and S-M 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 LV 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 found to be $1\times10^8 \text{ cm/s}$, however in this value of $\mu_e$ was not taken into account. This work was supported by INTAS 97.1386 and NATO SP.I7/879 projects.

SESSION T2: III-NITRIDE DEVICES-ELECTRONIC

Chairs: Philip G. Neudeck and Mary H. Crawford

Tuesday Morning, April 25, 2018

Golden Gate A2 (Marriott)
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 the interface. The cutoff frequency of MOS/HEFETs grown on 4H-SC 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 10.5 km/s. High-frequency characteristics of MOS/HEFET are also equal or better than those for the HFET. These results clearly establish the potential of using the AlGaN/GaN MOS/HEFET devices for high-voltage high-temperature applications.

10:15 AM *T2.4
AlGaN BASED T/R MODULES. John C. Zolper. Office of Naval Research, Lexington, 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-quality and low-temperature growth 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 (> 500 V) 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 ASSEMBLED MBE. W.A. Y. Sharp, A.J. Simmons, S. Keller, U.K. Mishra. Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA; C.R. Ekoss, B. Heying, J.S. Speck. Materials Department, University of California, Santa Barbara, CA.

We report DC and RF characteristics of undoped AlGaN/GaN HFETs grown by RF plasma assisted MBE on sapphire substrate. The dependence of the spontaneous and piezoelectric polarization contributions to the 2DEG charge density was characterized as a function of the Al mole fraction (8%-27%) and the thickness of AlGaN layers. 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, gate length of 0.7 micron, maximum drain current exceeded 1 A/mm and measured unity current gain cutoff frequency was 22.5 GHz. Microstrip power densities measured using an ATN load pull system was 3.5 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 MOVCD-grown GaN-based HFETs on sapphire thus demonstrating the excellent capability of MBE grown GaN for microwave power applications.

11:00 AM *T2.6
POSSIBILITY OF GaN GUNN DEVICES FOR HIGH POWER GENERATION ABOVE 200 GHZ. Bidhan Karmakar, Yingming Zhu, SUNY at Stony Brook, Dept of Electrical and Computer Engineering, Stony Brook, NY; Yungi Coronas, RSM Sensitron, Deer Park, NY.

This paper investigates the potential of Gallium Nitride (GaN) Gunn diode for generating high power radiation at millimeter and submillimeter 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 was found that, similar to devices based on InP, the graded profile resulted in a much improved current density in terms of output power at a given operating temperature. In particular, a GaN Gunn structure consisting of a 1 µm thick active region with a graded doping profile increasing from 5 x 10$^{18}$ cm$^{-3}$ at the cathode terminal to 4 x 10$^{19}$ cm$^{-3}$ at the anode terminal yielded a maximum output voltage of 650 V, a maximum drain current of 8 A, 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 MSEE, Univ of Florida, Gainesville, FL; G. Zhang, A.P. Zhang, F. Ren, Dept Chemical Engineering, Univ of Florida, Gainesville, FL; S.J. Pearton, Dept MSEE, Univ of Florida, Gainesville, FL; J. Han, Sandia National Laboratories, Albuquerque, NM; J.A. Cao, Dept Chemical Engineering, National Central Univ, Chung-Li, TAIWAN.

GaN Schottky diode and p-n rectifiers were fabricated on a range of different MOVCD-grown material. Reverse breakdown voltages were typically in the range of 350-550 V for standard MOVCD layers, but can reach as high as 2 kV on in-situ metal. Figures-of-merit (V$_{BR}$/I$_{OFF}$) in the range of 5-50 MV/cm, emphasizing the potential of these devices for power switching applications. Unpassivated devices typically display a negative temperature coefficient for the reverse breakdown voltage. Current densities are typically higher in the p-n structures, as 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 Misic, Nguyen Nguyen, Danny Wong, Paul Hashimoto, Loren McGray, David Grider, Chinh 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 cutoff power density of 0.55 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 metalorganic molecular beam epitaxy. The structure used for HEMT fabrication was grown in following order: 10 nm thick AlN buffer layer, 2 µm thick GaN layer and 24 nm thick AlGaN Schottky barrier layer. The composition of AlGaN Schottky layer was empirically optimized to induce piezoelectric sheet charge of 1.2 x 10$^{13}$ cm$^{-2}$ on 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 0.5 W/mm that was measured for these devices at 8 GHz is the best to 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

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 impedances, large gate voltage swings, normal-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) to dope GaN with Al layer, we have obtained a good MIS capacitor with low interface state density and excellent high-frequency capacitance-voltage (CV) characteristics. However, for a semiconductor with a wide energy gap, the generation of minority carriers 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$_2$O$_3$/Si hetero-junction with PECVD-grown SO$_x$ as a gate insulator. The gate leakage current is lower than 10$^{-14}$ A at 10 volts and the gate breakdown voltage is higher than 20 V. 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/µm 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
Chair: Michael S. Solar and John C. Zolper
Tuesday Afternoon, April 25, 2000
Golden Gate A2 [Marriott]

1:30 PM T3.1

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 MBE on a 2×1 dense epitaxy using a rhpicos 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 C1/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 mA cm⁻² at 1 V, corresponding to power densities of 20.4 kW cm⁻² for the HBT structure. At 250°C, the maximum current density was 2.55 mA cm⁻² at ~4 V, corresponding to a power density of 10.2 kW cm⁻². Recent temperature common emitter gain for these devices was in the range of 15-30. The breakdown voltage in both types of devices decreased at higher temperatures, with less degradation in the BJT structure. In the common-base operation, Ic was approximately equal to 1.5 V, indicating high emitter injection efficiency. This mode of operation is attractive because of the possibility of power gain through implicate transformation.

2:00 PM T3.2

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. The GaN bipolar device suffers from high base resistance due to the relatively low hole concentrations obtained in p-GaN, an attractive alternative is the p+np 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+np bipolar junction transistor (BJT). The structure was grown by MOCVD on c-plane sapphire substrates and means formed by low damage Inductively Coupled Plasma etching. The device characteristics were measured up to 9 V of 65 V in the common base mode and at temperature up to 250 °C. Under all conditions, Ic ~ Ie indicated the high emitter injection efficiency. The offset voltage was ~2 V and the devices were operated up to power densities of 13.4 kW cm⁻².

2:15 PM T3.3

The wide band-gap, nitrided 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 diffusions to get sufficiently high p- and n- levels were thought to be responsible. Here we demonstrate the potential to design III-nitride HBTs with β > 100 by reducing the base thickness to overcome the problem of high recombination. 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 AlGaN/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. The results of these simulations show that improvement is possible by reducing the base thickness to 0.2 μm instead of 0.5 μm. The experimental Gummel plot from the initial large area HBT structure agrees well with simulation by using concentration-dependent minority carrier mobility and lifetime recombination rates 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 the minority carrier transit time through the base. Moderate improvement of the DC current gain (by a factor of ~2) is observed by reasoning 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 fields up to 4kV/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.

3:00 PM T3.4
ACCUMULATION HOLE LAYER IN INVERTED p+GaN/AlGaN HETEROSTRUCTURES. M.S. Sial, A.D. Bykovich and R. Gimsa, 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 400 K, the hole mobility is a weak function of temperature and varies from 5 to 3 cm²/Vs. The calculations account for spontaneous and piezoelectric polarizations, as well as for strain relaxation. The calculations show that the polarization changes can induce at 300 K to 400 K, the hole mobility is a weak function of temperature and varies from 5 to 3 cm²/Vs. The calculations account for spontaneous and piezoelectric polarizations, as well as for strain relaxation. The calculations show that the polarization changes can induce a hole g搬迁 only exist at high sheet hole concentrations (exceeding 10¹⁵ cm⁻²). For smaller densities the holes in the accumulation layer should have the same transport properties as 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 heterojunction bipolar transistors.

3:15 PM T3.5
AlGaN HETEROSTRUCTURES FROM MATERIALS RESEARCH TO LIGHT EMITTING DEVICES. A. Wagner, A. Ramakrishnan, H. Olsch, M. Kunzer, P. Schlotter, W. Pleutsch, R. Kiefer, U. Kaufmann, M. Maier and K. Kochler, Fraunhofer-Institut für Angewandte Festkörperphysik, 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 properties, which 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 0.38 to 3.8 μm wavelength range will be presented.

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

While the majority of nitride light emitting device development has focused on InGaN multiquantum well structures for visible wave-
SESSION T4: GROWTH AND CHARACTERIZATION OF WIDE-BANDGAP MATERIALS

8:30 AM T4.1
LOW TEMPERATURE LATERAL EPITAXIAL GROWTH OF SILICON CARBIDE ON SILICON
Chao-Danning Yang, S. Miyamoto, S. Nakamura, Y. Hojyo, and S. Inoue
Kyushu Institute of Technology, Dept. of Electronics and Information Science, Fukuoka, JAPAN

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 hexachlororodisilane (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 films and earlier work[1].


8:45 AM T4.2
SiC EPITAXIAL GROWTH ON POROUS SiC SUBSTRATES
G. Malysheva, S. F. Suwann, Emerging Materials Research Laboratory, Department of Electrical & Computer Engineering, University of Florida, Gainesville, FL, M. Mykhaylyk, 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 modification of commercial 4H-SiC (10001) Si-face off-axis wafers. 4H-SiC epilayers were grown on these porous SiC substrates using atmospheric pressure CVD at 1250°C and Si:C ratio of ~0.5. 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 HEXA-METHYLDISILANE. Masahisa Kato, Masaya Ishimura, Enako Arai, Nagoya Inst of Technology, Dept of Electrical and Computer Engineering, Aichi, JAPAN; Yauhao Mau, Ji Chen, Shigeo Ishii, Kyoto Inst of Technology, Dept of Electronics and Information Science, Kyoto, JAPAN; Yutaka Tokun, 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 SiH4+4H2 with H2 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 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(001) by atmospheric pressure CVD using HMDS at 1250°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, plane diodes were fabricated on the samples by evaporating Au as a Schottky contact.
and Al as an ohmic contact. Relatively thin epilayers (~2.3 μm) showed broad DLTS signals over a very wide temperature range (100K~280K). These signals are attributable to defects originating from the Si/Si interface and having activation energies distributed in a wide range. On the other hand, relatively thick epilayers (more than 2.5 μm) enable us to probe Si far away from the interface and showed only one DLTS peak near 290K. The net acceptor concentration in the undoped GaN film is about 0.25eV. For 3C-SiC grown from SiH₄+C₃H₄, defects with larger activation energies of about 0.36eV have been observed.

9:15 AM T4.4
NON-CONTACT CHARACTERIZATION OF RECOMBINATION PROCESSES IN 4H-SiC. K. Masuda, T.P. Chow, R. Gutmann, Renesas Medical Institute, Center for Intelligent Electronics and 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 photociuctivity technique. A 200-nm InGaAs layer is used to excite photons in the lightly-doped epilayer and the conductivity decay transient is measured by a 36-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 InGaAs intensities, only a single exponential decay is observed. At higher injection levels, a two-stage decay is present, with a slower decay time constant by the same low-intensity exponential. This behavior is consistent with a SRH recombination model, the 10-μm p-type layer exhibits a high lifetime (τₑ) of 400-ns and a low-level lifetime (τₑ) of 80-ns. This corresponds to a τₑ = ~3–30 ns, and τₑ = ~80–300 ns. The 10-μm n-type layer also exhibits a two-stage decay with τₑ = ~3–30 ns, and τₑ = ~80–300 ns. The low-level lifetime of the p-type sample increases exponentially with temperature with an activation energy of 0.008–0.5eV from 130–250K, and 0.004–0.02eV from 250–300K. P-type epilayers on 2.0-inch wafers were observed to have longer lifetimes than those on 1.375-inch wafers. The value of high-level lifetime (0.1–μm) measured in this study has led to the development of high-quality, fully-automatically-modulated 4H-SiC devices operating at high temperatures.

10:00 AM T4.5
GaN QUANTUM DOTS ON SAPPHIRE AND Si SUBSTRATES. Haili Meng, 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 photooluminescence experiments. The latter showing temperature dependence characteristic of strongly confined systems. After incorporation of Ge into both substrates and following similar steps, and some thin enough for vertical coupling were created. Strong polarization effects led to a sizeable red shift, which depends on the size of the dots. Dot showing blue (small dots) and red (large dots) shift have been prepared.

10:30 AM T4.6
OVERGROWTH OF PATTERNED AlₓGa₁₋ₓN NUCLEATION LAYERS ON SAPPHIRE SUBSTRATES. Roman Dimitrov, Vyacheslav Tlaskal, Michael Murphy, William Schaff, Les Estesmair, School of Electrical Engineering, Cornell University, NY; Oliver Ambacher, Claudia Misk, Alexander Lehmann, Aigang Link, Martin Stutzmann, Wafer Schottky Institute, TU Munich, GERMANY.

The strong internal electric fields in nitride based heterostructures, resulting from spontaneous and piezoelectric polarization at heterointerfaces, are the driving force behind heterointerfaces' abrupt change. The strong spontaneous and piezoelectric polarization, have a crucial effect on the electrical, and optical properties in these heterostructures. Due to the low contribution of band to the heterointerfaces, it is possible to use the two-dimensional electron gas (2DEG) with high sheet carrier concentrations in undoped AlGaN/GaN heterostructures to reduce the effective activation energy of the Mg-acceptor in AlGaN/GaN superlattices. The direction of the electron to the conduction band is determined by the polarization of the heterointerface. The high magnetic fields reduced the 2DEG in the AlGaN/GaN heterostructures strongly depends on the polarity, which can be GaN or N-face. High quality GaN grown on sapphire by MOCVD was found to be always Ga-face opposite to GaN deposited by MBE, which means the polarity is determined by the polarity of the 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 AlₓGa₁₋ₓN nucleation layers grown by MBE on sapphire and overgrown by MOCVD and PIMBSE 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 1 mm in diameter. In addition the demonstration of MBE is discussed. The growth of 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; Parker, S.M. Beding, North Carolina State University, Dept. of 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 report on an approach to determine the variation of CLT in these double heterostructures in the composition range 0% ≤ InGaN ≤ 20%. The approach we adopted to determine the value of CLT was to follow the evolution of the photoluminescence spectrum with the film’s InGaN well thickness. 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 InGaN thickness, the emission energy when either a step-function or 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 be noted that the CLTs obtained in this nitride system are much higher than those predicted by the energy or force balance model. In addition, we will report on the possible relaxation mechanisms in the InGaN films and other electrical properties associated with the relaxation process.

11:00 AM T4.8

High quality bulk GaN single crystal substrates are needed to obtain low defect density homoepitaxial layers. The high temperature growth approach tends to give GaN crystals that 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 BMD.

11:15 AM T4.9
LANTAL AND VERTICAL GROWTH STUDY IN THE INITIAL STAGES OF GaN GROWTH ON SAPPHIRE WITH ZnO BUFFER LAYER BY HYDRIDE VAPOR PHASE EPITAXY. Shaolin Gu, Gang Zhang, Long 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 course of the Hydride Vapor Phase Epitaxy Process (HVPE) of 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 ZnO with the overgrown GaN superlattice. The morphology and optical properties of GaN films. We characterize the initial stages of growth on these ZnO-based surfaces. A high supersaturation in the growth ambient favours a rapid nucleation on the substrate. A high lateral growth rate on the surface promotes coalescence of small nuclei. Rapid rates lead to improved material 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-EPIPLATIAL MBE GROWTH OF GALLIUM NITRIDE WITH A GALLIUM BUFFER LAYER, Yihwan Kim, Sudhir G. Subramanyan, Henrik Sorge, Jonathan Kreuger and Erke 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 use 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 300 nm thick GaN epilayers after deposition of a thin Ga buffer layer. The resulting films typically show electron Hall mobilities as high as μ=400 cm²/Vs (with a background carrier concentration of n = 4 x 10¹⁷ cm⁻³), which represents an outstanding value for a MBE-grown GaN layer on sapphire. Also, structural properties are significantly improved; the symmetric (101) X-ray rocking curve width is drastically reduced with respect to that of the reference GaN epilayer grown on a GaN buffer layer. It is proposed that an increased lattice mismatch by the buffer layer is the main reason for the growth and a 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 were also used to study the growth mechanism of GaN on the Ga buffer layer.

SESSION T5: GROWTH AND CHARACTERIZATION OF III-NITRIDES
Chair: Hadii Morkoc and Suzanne E. Mohney
Wednesday Afternoon, April 26, 2000
Golden Gate A2 (Marriott)

1:30 PM T5.1 MEASUREMENT OF TRANSIT TIME AND CARRIERTO VELOCITY UNDER HIGH ELECTRIC FIELD IN III-NITRIDE P-i-N DIODES, M. Wronski, H. Shen, U.S. Army Research Laboratory, Sensors and Electronic 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 magnetic-field technique that monitors the change in the electroabsorption spectrum of 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 MOVPE with no special preparation, the transit time drops with increasing electric field in the intermediate field regime (<100 kV/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 1.9x10⁷ cm/sec is attained at 255 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 OVERGROWTH GaN DEPENDENCIES ON EXCITATION CONDITION, III. E. M. Crepeau, Luning Yue, Dept. of Materials Science and Engineering, Lehigh University, Bethlehem, PA; J. Rumer, M. Schumer and J. T. Ferguson, EMCORE Corp., Somerton, NJ.

Yellow light [YL] emission is enhanced in comparison with near-UV [BL] emission when local current density is decreased by debiasing 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 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 intensity on scanned area parameters, in terms of the GaN materials properties.


We present our results on investigation of optical properties and nonequilibrium carrier dynamics in quaternary AlInGaN materials grown on sapphire substrates by low-pressure MOVPE. 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 5% 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 cw dye laser. A very high 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. The results were also obtained on deep insight into the localization process in AlInGaN 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 KINETICS IN GaN FILMS, M. Masa 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 1100 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-vacancies defects. Photocurrent detection with interdigitated electrodes were fabricated on such films. From the measurement of photocurrent gain, the mobility-lifetime product for each film was determined. The mobility-lifetime products were then used to determine the lifetime and the mobility. The 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. 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 resistivity of the films increased. Based on a model proposed by Rose, these results indicate the presence of nonlinear recombination and the mobility-lifetime product increases with increasing light intensity. These results together with previous discussed dependence of recombination lifetime on the position of the dark Fermi level are analyzed to derive the extent of the band tails in the films.


2:45 PM T5.5 OPTICAL CHARACTERISTICS OF HYDROGEN VAPOR PHASE EPITAXY (HVPE)-GROWN GaN, Eunsun Oh, Ighyoun Kim, Sungsoo Park, Jaeyong Han, Seongshik Lee, Kyujoel 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 dominant band emitted line at 3.40 eV is dominant, whose linewidth being broader than typical MOVPE-grown GaN. With increasing temperature another peak around 3.39 eV appears, whose relative
intensity with respect to near-band-edge emission increases with increasing temperature. At room temperature these two peaks overlap with each other, however by cooling, we observed a peak in the 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 subsurface damage. With the growth of a GaN layer on the indium surface either by HVPE or by MOCVD, the peak around 3.83-3.9 eV disappeared both in the PL and CL spectra. It was found that the CL intensity on the surface of the scanned area was stronger than that on the unscanned area during the polishing process. Besides the scanned 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 MIKE GROWTH - STRATEGIES, MATERIALS, AND PROPERTIES. J. P. Kotak, M. Heim, R. J.bi, R. J. Petrich, Robert J. Nemeth, North Carolina State University Dept. of Physics, Raleigh, NC; Robert F. Davis, North Carolina State Univ. Dept of Material Science and Engineering, Raleigh, NC.

AI N layers were grown on 6H-SiC(1001) with various nucleation procedures, V/H 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 MBE growth. A rich root 3 x root 3 SiC surfaces were also prepared using 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 - 950°C. The surface morphology of the AlN films observed by AFM was significantly changed by the nucleation procedure. When the growth was initiated with ammonia-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, the surface showed a high density of relatively large bumps. These features seemed to originate from SiN formation at the heteroeptificial interface. In this case, the growth rate in the vertical direction was higher than that of the Al rich growth initiated film. It was found that the control of the Si composition and V/H ratio as the growth interface is crucial for the AlN film quality.

3:45 PM T5.7 CHARACTERIZATION OF THIN GaN LAYERS DEPOSITED BY HYDRODE VAPOUR PHASE EPITAXY (HVPE) ON 6H-SiC STRATEGIES. J. T. Walz, J. T. Christiansen, D. C. Swann, School of Chemical Engineering, E. Koshia, S. E. Suddow, Emerging Materials Research Group, Department of Chemical Engineering, Mississippi State University; Yu. Melnik, V. Dmitriev, 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, there are not available and do not grow in size. SiC is an attractive substrate for epitaxial growth of GaN films exhibiting excellent lattice and thermal compatibility. In addition, due to high SiC thermal conductivity (~ 4 W/cmK) 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 heteroepitaxy. In this study, the nanoscale region and outermost atomic layer of nanoresolved thin GaN layers deposited by hydrode vapor 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 substrate sensitive techniques including atomic force microscopy (AFM), x-ray diffraction (XRD) in 2θ-2θ and RHEED measurements, 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 DISLOCATON MOVEMENT, NANOPHASE FORMATION AND NITROGEN SEGREGATION IN GaN. A. J. Kofod, K. K. K. Kimmel, National Center for Electron Microscopy, Lawrence Berkeley National Laboratory, Berkeley, CA; W. S. Wong and T. Sands, Department of Materials Science and 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 substrate using the laser lift-off process [Wong, et al.]. Secondary electron imaging and 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, these dislocation cores were seen to be in a stage of dislocation combination forming a dislocation network. Nanopipes were observed to glide on the dislocation cores on the 1/2<a> direction, leaving behind a hollow core. At these temperatures, no motion of these 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 insights into the process of defect formation of GaN at stresses temperatures near those used during electrical or deposition growth of GaN.


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 at 1064 nm that produced Maker fringes at 532 nm. Multidimensional least-squares fitting of the fringes permitted the simultaneous solution of the refractive index and birefringence at both 1064 and 532 nm, and the thickness of the GaN. The sample 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 18.9 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 considered acceptable for small quantities of material in all cases. The small bulk sample produced fringes 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 HETERO-STRUCTURES. Oliver Ambacher, Martin Stutzmann, Walter Schoenitz, Institute fur Materialphysik, GERMANY, Roman Dimitrov, Brian Fontz, Joseph Smart, Jim R. Shely, Michael Murphy, William Schaff and Les F. Eastman, School of Electrical Engineering, Cornell University, NY.

Two-dimensional electron gases in GaN/AlGaN/GaN heterostructures suitable for high electronic mobility transistors (HEMTs) are induced by strong polarization 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 number profiles and electrical transport properties of transistor structures by a combination of high resolution X-ray diffraction, atomic force microscopy, Pi-spectroscopy, Hall effect, C-V profiling and Shubnikov-de Haas measurements. The investigation of the AlGaN/GaN heterostructures 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 A. High electron mobilities of 50000 cm^2/V s were observed for 300 A barrier
materials of 1.1x10^15 cm^-3 at room temperature and 77 K.

By comparison of theoretical and experimental results we demonstrate
that the formation of the electron gas in these intentionally undoped and S-doped AlGaN/GaN structures both rely
on the difference of piezoelectric and spontaneous polarization
between the AlGaN and the GaN layer. The maximum sheet carrier
concentration found in the theoretical barrier model with a barrier
height of 300 A is limited to about 2x10^11 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
AlGaN/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 P.M. T5.11
HIGH ROOM-TEMPERATURE HOLE CONCENTRATIONS
ABOVE 10^11 cm^-2 IN Mg-DOPED InGaN/GaN SUPERLATTICES.
Kunihide Kamikura, Toshiki Makimoto, Naoki Kikuchi, NTT
Basic Research Laboratories, Kamikawa, JAPAN.

InGaN is an attractive material for blue light-emitting diodes
and laser diodes in 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 10^11 cm^-2. We have also reported that Mg-doped AlGaN/GaN
superlattices (SLs) show higher room-temperature hole concentrations
than Mg-doped InGaN thin film wafers. The former technique is
attributed to a hole-accepting electric 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_{0.2}Ga_{0.8}N/In_{0.8}Ga_{0.2}N SLs with high spatially averaged hole
concentrations above 10^11 cm^-2 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 thickness of InGaN and GaN were the same
thicknesses 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 x 10^13 cm^-2.
The hole concentrations of Mg-doped In_{0.2}Ga_{0.8}N/In_{0.8}Ga_{0.2}N SLs increased with the In molar fraction,
and we obtained a hole concentration of 3 x 10^11 cm^-3 at room temperature for the
In_{0.4}Ga_{0.6}N/In_{0.6}Ga_{0.4}N SLs. The activation energies for Mg-doped
InGaN/GaN, derived from the temperature dependence of resistivity,
are about 80 and 30 meV for In_{0.6}Ga_{0.4}N and In_{0.4}Ga_{0.6}N, respectively.

SESSION T6: POSTER SESSION: WIDE-BANDGAP DEVICES, MATERIALS, AND PROCESSING.
Chair: Randy J. Shul, Fur Ren, Wilfried Pletschen and
Masahiro Murakami.
Wednesday Evening, April 26, 1999
1:30-6 PM (Marriott)

T6.1 CHARACTERIZATION OF 3C-SiC FILMS GROWN BY CVD
CARBONIZATION OF Si(100) SUBSTRATES. J.T. Wolf, J.T.
Christensen, Dave C. Swalm, School of Chemical Engineering; M.S.
Mazulon, 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
as-exposed thin 3C-SiC film grown on a 5μm (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 utilizing a propylene-hydrogen mix [3% (CH4)
in ultrahigh-purity hydrogen] with a hydrogen carrier. 2D-Angle
resolved X-ray photoelectron spectroscopy (ARXPS), Auger electron
spectroscopy (AES) and ion scattering spectroscopy (ISS) were
performed on these films to identify the materials 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
evaluate film structure, surface morphology and film thickness
were performed for the substrate layers.

S.E. Sadow, M.E. Okhuryaev, M.S. Mazulon, M. Dudley, X.R.
Hung, W. Huang and M. Shamsuzzooh. Proceedings of the Materials

T6.2 THE GROWTH AND INVESTIGATION OF SILICONE CARBIDE
THIN FILMS OBTAINED BY PLASMA ASSISTED CHEMICAL
VAPOR DEPOSITION. Zbigniew Parys, S. Szudzik, Arturs Arankelyan, Emmanu
Arankelyan, Svetlana Berberes, Semhik Vosnyuk, Yeremia Yenigbeny, Gogik Mirzyan, Anne 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 partially 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 fields, was used. The ions of carbon, being accelerated and
focused in 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 (15000-30000V), 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=35-65mA), which can be influenced by the rate of flow of streams of
CH3H2 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 3C-SiC. The thickness of films was determined
by interferometer of reflected light. Obtained films with a thickness
~1 μm, where n is refractive index, and the wavelength of irradiation,
8 cm in 800 nm, can be used as unreflected, 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 λ=550 nm. In parallel, the resistance of devices towards
mechanical, chemical and atmospheric influences grows, thus resulting
in their longer lifetime. Also the total 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 SUBSTRATES. G.E. Carter,
G. Melcher, S.E. Sadow, Mississippi State University, Emerging
Materials Research Laboratory, Department of Electrical & Computer
Engineering, Mississippi State, MS; T. Zheleva, B. Gei, J. Jones,
Sensors and Electronic Devices Directorate, Army Research Laboratory,
Adelphi, MD.

Pendecy epitaxy of cubic SiC (3C-SiC) on (111) oriented Si wafers
was conducted in a cold-wall chemical vapor deposition (CVD)
reactor. First the 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 PENDEO film were placed on the
(100) Si wafer. The stripes were 5 to 8 microns in width and 1 micron in
length. The period of the mask was 10 microns, thus the unmasked area of PENDEO wafers was 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 10 μm ITO mask was then stripped and Pendecy
epitaxy growth conducted at a temperature of 1310 degrees C for 10 and
90 minutes under the following conditions: hydrogen carrier flow of
4.5 slm, S/C = 0.25 with a silane flow of 6 sccm and propylene flow
of 7 sccm. (both precursor gases are 3 percent in 97 percent UHP
hydrogen). After growth the samples were characterized using both
SEM, TEM, and XRD. The data indicated that PENDEO growth
was performed and will be presented. The first time, Pendecy
episotaxy of 3C-SiC on Si have been successfully performed. In this
data this preliminary experiments, including film confluence
experiments currently under way, will be discussed.

References:
Hung, W. Huang and M. Shamsuzzooh, Proceedings of the Materials
Sadow, "Preliminary Investigation of 3C-SiC on Silicon for
Biomedical Applications", International Conference on SiC and

T6.4 THE TEMPERATURE DEPENDENT BREAKDOWN VOLTAGE FOR
4H- AND 6H-SiC HETEROACTCES. Yoon-Sang Lee, Min-Koo Han and
Yoon-Ho Cho*, School of Electrical Eng., Seoul Nat 1 Univ.,
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 performance. These devices have often shown the best breakdown voltage performance and temperature characteristics even in the similar cases, which may result from the defects of SiC such as microcavity, 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 diode.

Recently, the reliable and accurate impact ionization coefficients of different SiC were reported in various temperatures in almost ideal situation. We propose the closed-formed solutions for the temperature dependent breakdown voltage for 4H- and 6H-SiC diodes in order to suggest the easy sensitivity analysis breakdown voltages of many kinds of SiC in an arbitrary temperature by employing the accurate hole impact ionization coefficient and by reformed impact ionization integral. This could have the identifications in that previously reported other papers were the breakdown voltage analysis mainly in the non-rectruched cases and they did not include the temperature factors. The main process consists of two parts. One is the estimation of Fermi level 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-recruched diode (NRD) and recruched diode according to the electric field distribution. The good agreements between measured data and the derived 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. 

$P_{i} \exp(\int_{0}^{x} a_{i}(E) \, dx)$ where 

$\alpha_{p}(E) = a_{p} \times M(T)$

$\alpha_{n}(E) = a_{n} \times M(T)$

$V_n = 5.49 \times 10^{15} \text{M}^{-1} \text{T}^{-1}$

$W_n = 5.315 \times 10^{14} \text{M}^{-1} \text{T}^{-1}$

$V_B = 9.494 \times 10^{15} \text{M}^{-1} \text{T}^{-1}$

$W_B = 4.986 \times 10^{14} \text{M}^{-1} \text{T}^{-1}$

6T.5 A STUDY OF Pt/AIN/SiC MIS STRUCTURES FOR DEVICE APPLICATIONS

Margaret 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 Hwang and Gregory W. Aumer, Dept. of Electrical and Computer Engineering, Wayne State University, Detroit, MI.

AIN 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/AIN/SiC MIS structures. The AIN 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 HRSEM and XRD. Current-voltage and capacitance-voltage measurements were performed as a function of temperature. Most of the MIS structures showed rectifying 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 AIN films. The MIS structures were tested for use as low and high temperature hydrogen and hydrocarbon sensors.

6T.6 IMPROVED SENSITIVITY SiC HYDROGEN SENSOR


Silicon carbide is intended for use in fabrication of high temperature, efficient hydrogen sensors. Traditionally, when palladium coating is applied on the exposed surface of SiC, the chemical reaction between palladium and hydrogen produces a detectable change in the surface chemistry that can be monitored to produce a reaction that is also as well as a palladium implanted SiC sensor. The palladium implantation was done at 500°C into the Si face of 6H-SiC at various energies and at various fluences. Then, we measured the hydrogen sensitivity response with this fabricated sensor. This was done by exposing the sensors to hydrogen while monitoring the current flow through 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 Pt implantation has revealed a noticeably different behavior than the SiC sensors produced by Pt deposition. In the Pt deposited SiC sensors, as well as in the ones reported in the literature, the current rise in the presence of hydrogen at room temperature as well as at elevated temperatures. In this case, 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.

6T.7 HALL EFFECT MEASUREMENT AT LOW TEMPERATURE OF AN AMPLIFIED IMPLOTTED SiC:-deals.

Jani Benzeni, Rongji, Tominagiku, Takanaka, R&D Association for Future Electronic Devices, Tukuba, JAPAN; Yukui Ishikawa, Yamomori Takanaka, Hikone, Japan, Nozomi Kohyama, Kiyoto, Arai, Electrotechnical Laboratory, Tukuba, 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 223 Ω/sq. was achieved in the simple, which implanted at 500°C and subsequently annealed at 1800°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(001) substrates with 8° off-angle and a single epitaxial layer was used. With multiple energy implantation (4kV-80keV) was performed at substrate temperature of 500°C in order to form a box-shaped profile with depth of 83 nm. The total dose of 1×10¹⁴ cm⁻² and 7×10¹⁵ cm⁻². Then, samples were annealed at 1800°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 (7×10¹⁵ cm⁻²) implanted sample, electron concentration is almost invariant with temperature. This indicates the formation of metallic conduction layer. On the other hand, samples with less than 1×10¹⁵ 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.

6T.8 METALLIZATION OF SiC BY HIGH DOSE IMPLANTATION OF Ti, Mo, AND W IONS USING A MEVVA ION SOURCE.

J.K.N. Lindner, Universitat Augsburg, Institut fur Physik, Augsburg, GERMANY; K. Baba, R. Hunszt, Technology Center of Nagasaki, Hiden, Omurashi, Naogaki, JAPAN; B. Stritze, Universitat Augsburg, Institut fur Physik, Augsburg, GERMANY.

Transition metal silicides and carbides are possible candidates for future high temperature contacts on silicon carbide. Therefore, the investigation of transition metal ions 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 SiC:SiC substrates upon high-dose implantation using a metal vapour vacuum arc (MEVVA) ion source is studied. MEVVA ion plating provides 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 polycrystalline 3C-SiC were implanted at temperatures of 260 and 500°C with 1×10¹⁴ ions cm⁻² of Ti, Mo, and W ions, respectively, at a constant voltage of 60 kV and with doses up to 2×10¹⁵ 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. High resolution X-ray photoelectron spectroscopy, XPS, was applied to determine the bonding state of Si, C and metal atoms, and grazing incidence XRD was employed to monitor the presence of crystalline phases. Cross-sectional TEM and energy filtered TEM were used to reveal the microstructure of selected samples. Results are discussed in terms of potential application of high-dose metal implantation for SiC metallization purposes.

6T.9 THE FORMATION AND CHARACTERIZATION OF EPITAXIAL TITANIUM CARBIDE CONTACTS TO 4H- SiC.

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

An important technological problem currently limiting device performance is some instances in 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 use processes. In this work, Ti/Cr Ohmic contacts to n-type 4H-SiC formed by a simultaneous low pressure chemical vapor deposition (LPCVD) Ti and Cr co- evaporation with Ti and Cr at low temperature (< 500°C). We report typical TSC contact formation on 4H-SiC. We achieved a contact resistance of 1.07 x 10^-6Ω cm^2 for Ti/Cr Ohmic contacts on Al implanted Silicon carbide. The rectifying behavior of Ti/Cr Schottky contacts was also investigated using L-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 Ti/Cr epitaxial layer.

T6.10
MICROMACHINING OF SiC WITH SHORT AND ULTRASHORT LASER PULSES. Deepak Sengupta, Kolja Nickhaus and Arminnda Kaur, 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 drilling, lines, circles and boxes on the surface of bulk SiC by the use of short and ultrashort laser pulses. These structures will be atomically smooth and will scale on bulk SiC. This will 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 nonlinear ionization. The structures will be checked for defects, edge quality and cracks with light, white light, atomic force and scanning electron microscopy. The accuracy of the structures will be discussed as a function of pulse duration (and wavelength).

T6.11
ARSENCIC INOCULATION IN GALLIUMNITRIDE GROWN BY METAL ORGANIC CHEMICAL VAPOR DEPOSITION USING DIMETHYLHYDRAZINE AND TERTIARYBUTYLABARINE. S. Kellermann, K.-M. Yu, E.E. Haller, and E.D. Borel, Courchesne, 2, Department of Materials Science and Mineral Engineering, University of California, Berkeley, CA; 2Center 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 high band gap bowing. However the synthesis of this ternary alloy is difficult due to phase separation at relatively low concentrations of In in GaAs and As in GaN. 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 (DMH) as source of nitrogen. Tertiarybutylamine (TBA) and triethylgallium (TEG) were the other source materials. Device quality GaN grown by MOCVD commonly uses ammonia (N-source) which usually requires reaction temperatures of more than 1000°C and molar flow ratios [V]/[III] of around 5000. DMH 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 0.01 to 0.1. They were deposited on top of undoped GaN layers and then capped with a thin undoped GaN layer also grown at 900°C with a [V]/[III] ratio of 57. Secondary ion mass spectroscopy (SIMS) data reveals a strong decline in As incorporation with increasing growth temperatures from 800°C to 900°C. Changing the [As]/[V] ratio from 0.01 to 0.07 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 lower temperature cases, 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. This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-76SF00098.

T6.12
PENETO-EPI TYPY OF GaN ON Si SUBSTRATES: A FINITE ELEMENT ANALYSIS. Wael Ashour and Kenneth A. Jones. North Carolina State University, Department of Mechanical Engineering, Raleigh, NC; US Army Research Laboratory, CISED, 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. Penedo-epitaxy of GaN on 4H-SiC substrates followed as an alternative to the conventional LEO technique, via etching columns along 11-20 direction in the underlying GaN layer. However, the column reduction and growth on cooling, as well as it’s role for the difference in the dislocation density distribution within the structures, it was shown that the pene-epitaxy of GaN can be achieved not only on 4H-SiC, but on Si substrates, as well.2. The present study uses Finite Element Approach for stress analysis of pene-epitaxial GaN Structures, on Si substrate and utilizing transformation 3C-SiC layer. The model uses symmetric boundary conditions along the 11-20 side for surface condition and for boundary conditions for the bottom of the heterostructure. Stresses and strains are evaluated considering Hookan elasticity model, fixed elastic constants and considering only the mismatches in thermal expansion coefficients among the phases in the heterostructures. 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 AIN/SC-Si/Si interfaces.

T6.13

Low resistivity ohmic contacts are difficult to form to p-type GaN and AlGaN due to the unavailability of high quality growth methods for GaN and AlGaN and p-type carbon-doped GaN regrowth on p-GaN prior to ohmic metallization has been shown to improve contact resistance in p-GaAs. Applying the regrowth method to the p-base regions of ngn 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^-18 cm^-3) was grown on the devices (~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 pressure conditions with a Cl2/Ar chemistry. SO2 was used for emitter sidewall formation to prevent 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 thick GaN at low-temperature (LT) is characterized by an island growth with a highly defective layer. When a subsequent GaN layer is deposited at high-temperature on top of this LT-GaN layer, island growth takes place in between islands. The goal of this growth method is to improve the quality of the LT-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 LT-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 LT-GaN layer. While increasing the growth temperature of the LT-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. Schwiezer, M. Niebus, L. Molo, P. Brogemeir, S. Koynow, Physics Department, Instituto Superior Técnico, Lisbon, PORTUGAL; M. Hesken, Aixtron GmbH, Andech, 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 spectra range after pulsed laser annealing. For comparison, the same samples were also analyzed in the secondary photocurrent mode, where it is known that persistent photocurrent affects the detector performance and slow detector response. The samples were deposited 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 high temperature photoluminescence, photocurrent and photoluminescence spectroscopy, and Hall measurements. The carrier densities at room temperature range from 3x10^{16} to 4x10^{18} cm^{-3} depending on Al content. The surface structure of the MOVPE-grown AlGaN and the metal contacts were analyzed by AFM. Carriers were generated with green (522 nm) and UV (266 nm) pulses of a Nd:YAG laser system. The secondary photocurrent transients showed a slow decay reaching the steady state after both green and UV laser excitation.[2] Apart from small lateral effects near the contacts no signal at zero-applied bias was 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 behavior 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. Hasegawa, et al., Appl. Phys. Lett. 97, 163503. [2] D. Montero et al., 3rd Int. Conf. On Nitrile Semiconductors (ICNS3), Nice, 1999.

**T6.16 COMPARISON OF DIFFERENT SUBSTRATE PRE-TREATMENTS ON THE QUALITY OF GaN FILM GROWTH ON 4H-, 6H-, 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 SiC, 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%). 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] preoxidation with NH3 for 0.20 min, [b] pre-adsorption of TMG or TMA for 0.5-5 min, and [c] deposition of AlN buffer layers of different thicknesses at 1100-1150°C. After each pre-treatment, GaN was deposited by MOCVD using diilute H2 [Ar + 12%H2] and DMG. All-Al metal organic source 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 ultrathin (3-nm) layer 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 deposition was for longer than 3 min (up to 10 min), GaN/V1 AlN/SiC heterostructures was obtained. In case of the ultrathin layer of AlN, epitaxial GaN was successfully deposited on 6H-SiC (200), 4H-SiC (200), and 3C-SiC/Si [111] substrates. The thickness 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 4H-SiC BY MO-MBE USING MOVPE-GROWN AIGaN.** Tehei Honda, Tomohiro Takezawa, Yonichii Yamamoto, Kyoosuke Miaki and Hiroki Kawaiishi, Dept. of Electronic Engineering, Kogakuin U., Tokyo, JAPAN.

The tact constants of GaN layers along the a-axis were estimated using RHEED patterns during metal-organic molecular beam epitaxy (MO-MBE) growth. The nucleus area for the growth was used for the gallium and nitrogen sources, respectively. The GaN layers were grown on 4H-SiC with and without AlGaN layer grown by metal-organic vapor phase epitaxy (MOVPE). The RHEED pattern of MOVPE-grown GaN on the AlGaN buffer was 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. Suzuki et al., JAP, 75, 2924) that the (0 0 0 1) GaN layers (GaN layers grown by MOVPE) were a smooth surface layer. 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 4H-SiC without any buffer layer, the mixture of hexagonal and cubic phase was observed in RHEED patterns. This may be due to the surface of 6H-SiC with steps, which have cubic and hexagonal subunit cells. Those mixture phases indicate that there were standing faceting defects on the layers.

**T6.18 DISLOCATIONS IN DEFECTED 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.

AIN, 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 hydrophane vapor epitaxy (HVPE), it is possible to grow relatively thick single crystal GaN films (with a thickness of 100-800μm) which are free of dislocations in HVPE GaN crystals and investigated their indentation behavior as a function of temperature and load. In previous study,[1] it was reported that Vickers indentation of the [0001]-oriented GaN thin films produced a dependence of stress and strain on the indentation load for various crystals.

**T6.19 MOVC GROWTH AND MAGNETO-TRANSPORT STUDIES OF AlGaN/GaN HETEROSTRUCTURES GROWN ON SAPPHIRE SUBSTRATES.** Tho. Wong, D. Nakagawa, J. Imai, 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 U., 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 10^5 cm^2/Vs grown on sapphire substrates. The GaN electron effective mass and the quantum scattering time are determined by well resolved Shubnikov-de Hass oscillations. The electron effective mass is determined to be 1.0m_0 and 0.24m_0 for the 2DEG in Al0.18Ga0.82N/GaN single heterostructure (SH) and Al0.6Ga0.33N/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 elastic scattering time to the quantum scattering time increases with increasing 2DEG sheet carrier density, which agrees very well with the prediction calculation based on the piezoelectric effect from the piezoelectric coefficient. Our results indicate that a low density of deep centers may result in this much higher mobility of our structures compared with others, which is probably due to the high quality of 2DEG samples. This result can also well explain our previous report that the mobility dramatically decreases if the AlGaN layer is doped by silicon.

T6.20 FORMATION AND CHARACTERIZATION OF OXIDES ON GaN SURFACES. D. Misteke, T. Poter, F. Fedler, H. Khosang, O.K. Semchikin, J. Steimer, J. Aderhold and J. Graf, 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 O2-atmospheres at various temperatures. These methods modulate traps which with the increase of temperature decrease.

The photoelectrochemical oxidation takes place in aqueous solution of potassium hydroxide for pH values ≤ 12.8. 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 potential in the 3-electrode configuration. Homogeneous 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 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 Ga2O3 is formed with an attributed stoichiometry of Ga2O3. Secondly, depth profiling by Ar sputtering shows the oxide thickness to be dependent on the photoanodic voltage. Additionally, an energy shift of the Ga2M4a-M4a Auger-electron peak to lower values has been detected for all GaOx 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 layers in a modelized GaN.[1]

Annealing GaN in O2-atmospheres above 900°C also leads to surfaces fully covered with Ga2O3. We found that N-polar surfaces oxidize faster than Ga-polar surfaces, which is in agreement to the theoretical work of [2].

The usage of these oxide layers as dielectrics will be discussed.


T6.21 FERMI LEVEL POSITION AT THE AlGaN SURFACE IN AlGaN/GaN HETEROSTRUCTURES. Robert A. Lanzer, Angela Rizzi, and Hans Lüth, ISF 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] with 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 UHV system. The measured spectra have been compared to the valence band maximum (VBM) of AlGaN/GaN heterostructures, as gained by the XPS experiments. Electrical measurements, Hall effect and CV profiling have been performed and the results are correlated to the information on the boundary conditions and on the microscopic 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. Xiaqing Shen, Toshikido Ide, Sung-Hwan Cho, Mitsumasa Shimizu, Shiro Hiro 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 electrical and optical properties of the films. Characterizations by CBE, HXPS, chemical etching and RHEED indicated that Ga-polarity films were always obtained from samples grown by MOCVD, while the lattice orientation of Ga-polarity grown films is not as clearly defined. 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 layers processes at the initial stage by RHEED. Low temperature (LT=550°C) and high temperature (HT=700°C) GaN and AlN buffer layers were performed at the initial growth stage. Direct characterizing of surface reflection electron spectroscopy (CARS) technique, together with RHEED surface morphology observation, several 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 suggested in a future paper, that AlN buffer layer with AlN/GaN/GaN in AlN high temperature (HT=700°C) buffer layer in r-MBE. XRD rocking curve showed that the FWHM of GaN film with Ga-polarity was decreased to about half of that with Ga-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. Sanya, Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, HONG KONG.

Low frequency noise is investigated in n-GaN films grown by rf plasma assisted molecular beam epitaxy. The temperature dependence of the voltage noise power spectra S(v) was examined from 400K to 60K in the frequency range between 80Hz and 1GHz. The S(v) dependence is modeled as the superposition of 1/f (Flicker) noise and a Lorenzian (GR) noise. For the Flicker noise the k0 constant is around 4, which indicates that the level is 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 site states near the band edges, and the GR noise should be correlated to the capture and emission of electrons by single level traps. The Arrhenius fit of the frequency and time constant indicates the GR noise arises from traps on energy level of 118meV from the band edge.

T6.24 MONTE CARLO BASED CALCULATION OF TRANSPORT PARAMETERS FOR WIDE BAND GAP DEVICE SIMULATION. Enrico Bellotti, Munzir Farhaim, 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 Electrical, 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 continuous time random walkers. Calculations are made for the wurtzite and zinc-blende 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, impact ionization, and drift mobility in the high field limit. For GaN, we also compare the calculated mobility 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 in several different AlGaN/GaN based n-p-n heterojunction bipolar transistor structures. These are examined through calculations of their band profiles and minority 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 minority carrier concentrations of several AlGaN/GaN HBT structure are calculated self-consistently in a semi-classical approximation taking into account the polarization charges, charge 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. To support this, 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 IL-NITRIDE HETEROSTRUCTURE FIELD EFFECT TRANSISTORS.** T. Li, P.P. Ruden, Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN; M.D. Johnson, M.G. Acs, Electron Science and Technology Division, Naval Research Laboratory, Washington, DC.

The output characteristics of IL-Nitride semiconductor heterostructure field effect transistors (HFETs) are strongly dependent on the ambient temperature of the channel region due to relatively large variations in both the drift velocity and the voltage in the device. 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 use of 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 IL-Nitride and substrate thermal conductivities through the technique of self-consistent boundary conditions. The results of this thermal model are then used to calculate the DC output characteristics of several different device designs. It is shown that improvements in temperature management can have a large positive impact on the performance of IL-Nitride HFETs.

**T6.27**
**CHARACTERISTIC OF OPTICAL PROPERTY AND DEFECT ANALYSIS IN InGaN-BASED LIGHT EMITTING DIODES.** C.P. Ling, H. Chang, Department of Electronics and 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 well (MQW) LED structures were studied. The characteristics of PL and electron luminescence (EL) spectra of both structures were measured by using the pumping laser power and injection current, respectively. The blue emission peak of PL spectra from InGaN/GaN DH structure and InGaN MQW were appeared at 470nm and 479nm, respectively. The FWHM and the peakemission wavelength were 25nm and 470nm at 11mW laser excitation power. The blue emission of InGaN/GaN 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 479nm 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) increased and the 479nm peak (Zn-acceptor states) saturated with the high injecting DC current in DH-LED structures. The EL intensity of 429nm peak (band-edge emission of InGaN) and the 479nm peak (Zn-acceptor states) saturated with the high injected current and the EL intensity ratio of 429nm/479nm peaks were raised by increasing the injection current. In MQW-LED structures, the EL spectra at 450nm with 20mW linewidth showed 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 (Dfd) 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 0.12mW and 10mW at 20mA.

**T6.28**
**LONG-LIFE CONSTANT TRAP EFFECTS IN AlGaN/GaN HFETs.** Xiaoming Deng, Peter M. Asbeck, T.Y. Yu, University of California at Los Angeles, Electrical and Computer Engineering, LA Jolla, CA; M. Froudakis, M.G. Acs, Electron Science and Technology Division, Naval Research Laboratory, Washington, DC.

AlGaN/GaN HFETs 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 potential benefits into practical devices is required for optimization of microwave device performance. 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 HFETs. Measurements under pulsed conditions show 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 milliseconds. A 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 conduction band 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 GaN buffer layers.

Support for this work was provided by BMDO (Dr. Kepi Wu) monitored by USA/ASDC.


**T6.29**
**AlGaN/GaN HEMTs WITH EXTREMELY SHORT GATE LENGTH.** Oliver Breitbach, Hedi Greiter-Klingler, Bertram Kuhn, Ferdinand Scholz, Heinrich Schwierz, 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 frequency. To achieve high speed operation with transistors the time constant of the RC circuit [R represents the gate resistance and C the gate capacitance] 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 shorted 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 have 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 devices. The 70 nm HEMTs have a 3-dB cutoff frequency of 90 GHz and an 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 CRYOTRON RESONANCE EXCITED N2 PLASMA SOURCE.** J.T. Hauch, G. Breitbach, J. Rattner, H. Schwierz 4. Physikalisches Institut, Universität Stuttgart, Stuttgart, GERMANY.

The short-time electron cryotron 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 the 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 treatment affect on Ar ion beam etched GaN samples was also examined. We adopted Taguchi orthogonal table design to optimize the ECR nitrogen plasma parameters with respect to VI 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 normal experimental methods. It is clearly indicated that the radio frequency (RF) power play the most important role in the surface passivation of ion beam etched GaN. After nitrogen plasma treatment, the diode reverse breakdown voltage is drastically increased from 15V to 90V. The lowest leakage current is achieved with 600μW microwave power, 0.5 mTorr nitrogen pressure and 30W RF power for 3 minutes. With the aid of nitrogen plasma
II-VI nitrides are promising materials not only for optical devices in the blue-green spectral region, 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/Al 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 X-ray diffraction, Pd [111] metal grew epitaxially on GaN [001] surfaces with Pd [110]/GaN[112]. The closed-packed atomic planes of the Pd film were well ordered in surface normal direction as well as in the in-plane direction. On the other hand, other metal such as Au, Ag, Cu, or 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 closely related to the in-plane epitaxial quality of metal on p-GaN.

T6.31 GAN/NITRIDE STRUCTURE FORMATION MECHANISM OF Pd-BASED CONTACT TO p-GaN: Doo-Woo Kim, Jong Cheol Bae, Won Jin Kim, Hong Keo Baik, Dept of Metallurgical Engineering, Yonsei University, Seoul, KOREA; Chang Hee Hong, Dept. of Semiconductor 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, Jeonju, KOREA.

etching with respect to mobility, sheet resistance and sheet electron concentration. The mobility after etching decreases dramatically at small angles and remains nearly constant 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 and angled etched for angles larger than 40 degree. The sheet electron concentration decreases independently of the etching angle up to 20% 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 phenomenon. Furthermore, we also observed that a 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 NITRIDE AND BORIDES ON GaN: Jack Jasinski, Lawrence Berkeley National Laboratory, Materials Science Division, Berkeley, CA; Institute of Experimental Physics, Warsaw University, Warsaw, POLAND; E. Kamińska, A. Piotrowska, A. Biercz, Institute of Electronic 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 radio frequency magnetron sputtering from Ti target in argon atmosphere. ZrB 2 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 only of GaN proximity, 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 HRTEM methods, SMS 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 of the samples, thus enabling high-quality capping layers. The thermal stability can be further improved up to 1200°C by the use of multilayer coatings.


Thermal expansion and lattice parameters are important thermo-physical 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 2 O 3, ZrO 2, and Gd 2 O 3 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, Melbourn, AUSTRALIA; Geoffrey R. Reeves and Anthony S. Holland, BMT, Dept. of Communication and Electronic Engineering, Melbourne, AUSTRALIA.

A major issue in the realization 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 gases. To date, the most thorough investigation is 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 IIE 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 gases. We have also examined the effect on etch rate of varying the ratio of the O₂/Ar mixtures. The etching of the diamond film by O₂ and O₃ 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 film in O₂ and Ar 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 O₂ in the O₂/Ar plasma resulted in a proportional increase in the etch rate due to an increasing contribution from ion-enhanced chemical etching.

**SESSION T7: PROCESSING OF ILNITRIDES MATERIALS**

Chair: Melanie W. Cole and Kenneth A. Jones

Thursday, April 27, 2000

Golden Gate A2 (Marriott)

**8:30 AM #T7.1**

**DEVICE PROCESSING FOR GaN HIGH POWER ELECTRONICS**


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

**9:00 AM #T7.2**

**CONTACT STO AIGaN**

Suranne Moloney, Eric Readiger, The Pennsylvania State University, Dept of Materials Science and Engineering, University Park, PA.

Contacts to AIGaN 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 have determined that the rol, metal type, contact type and current density. The primary goal of this study has been to understand the influence of the contact morphology and the contact on the device performance. Using both contact formation schemes to n-type AIGaN, we 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. Ashbeck 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-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 ohmic characteristics of different contacts to P-GaN were investigated. We examined various surface treatments, including HF, HCl, aqueous 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 aqueous was more effective in improving 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 N₂. It was found that preannealing in N₂ at high pressure for an extended period (e.g., longer than 20 minutes at high temperatures) is detrimental to the contact characteristics. Preannealing in forming gas following by annealing in N₂ 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 on GaN creates the best ohmic contact with the 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 region of the sample. Ga vacancies were observed to cause poor current spreading in p-GaN. The Au(8000 Å)/Ni(300A)/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**

**ELECTRICAL MORPHOLOGY STUDIES OF OHMIC CONTACTS ON AlGaN/GaN HETEROSTRUCTURES**

Vladyslav Tikh, Roman Dimitrov, Michael Murphy, Joe Smart, William Schiff, James Shenly, 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, so low source resistance is needed for good $r_g$ values. Although we have achieved a transfer resistance of 0.35 Ω mm and $r_g$ of 5.6-7 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 nonlinearity of these devices in low applications. Ohmic contact recipes consists of a combination of high and low current density. We have found that the best ratio of Ti/Al from 0 to 2 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 of morphology and electrical characteristics the addition of a refractory metal to the Ti/Al system.

**10:00 AM #T7.5**

**INDUCTIVELY COUPLED HIGH-DENSITY PLASMA-INDUCED ETCH DAMAGE OF GaN MESFETs'**

R.J. Sull, L. Zhang, A.G. Baca, C.G. Williams 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-induced removal of the material. Under conditions of both high plasma flux and energetic ion bombardment, GaN etch rates greater than 500 μm/min and anisotropic etch profiles are readily achieved in Inductively Coupled Plasma (ICP) etching 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 usability 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 be 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.

**10:45 AM #T7.6**

**ETCH DAMAGE ASSOCIATED WITH ION CHANNING IN GaN**


Surface damage observed on GaN samples can be attributed to a combination of ion channelling and charge displacement effects. The ion channelling effect occurs when high energy ions pass through a material and are directed along the crystallographic axes of the target material. Ion channelling can result in the formation of damage zones that are several microns in length and several thousand angstroms in depth. The charge displacement effect occurs when high energy ions ionize atoms in the target material and create an electrical field that can induce surface damage. The interaction of these two effects can result in the formation of damage zones that are several microns in length and several thousand angstroms in depth. The interaction of these two effects can result in the formation of damage zones that are several microns in length and several thousand angstroms in depth.
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. One of the most effective experimental techniques to study the surface damage is the use of quantitative x-ray photoelectron spectroscopy (QXPS) to probe the sub-surface distribution of ion-induced damage. The QXPS were performed using a He-Cd laser as an excitation source. The amount of damage was quantified by comparing the maximum PL intensity before and after the etch. The decrease in PL intensity was associated with a degradation in the InGaN quantum wells. The extent of the damage was much greater than that 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 quantum wells bombarded by ions as 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

Photoelectrochemical (PEC) wet etching is a technique that has had extensive application in the patterning of the chemically inert GaN material. The technique has demonstrated the possibility of carrying out dopant-selective and bandgap-selective etching, achieving vertical etch rates of several thousand microns per minute. The presence of a higher bandgap substrate for many GaN structures allows the possibility of carrying out PEC etching by illumination of the material through the higher bandgap 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 cantilevers 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 occurs along the channeling axes in the material. We will discuss differences in mechanisms of frontside and backside etching, as determined using a KOH-based (11%) solution. We will also examine the selectivities and etch profiles of various MOCD-GaN structures, and discuss the etch rates. GaN samples etched in thickness from a few microns thick (MOCD-GaN) to over 30 microns (HVEG-grown). All selectivity studies were performed on MOCD-GaN samples with structures ranging in complexity from simple p-n junctions to BJTs and InN-like structures.

11:15 AM T7.8

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 MOCD-grown n-type GaN samples of 2 μm thickness and doped to approximately 10¹⁷ cm⁻³. Planar resistors of Hall-bar structures were fabricated by photolithography patterning followed by ICP etching. Ti/AI 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 scheme on the damaged sample and an untreated sample from the same wafer. An almost an order of magnitude reduction of noise spectral density was observed from the damaged sample compared to the undamaged sample which is well in line with the assumption that the quality of the material, yet is unlikely that the etching process would contribute to reduction of defects. In fact dislocations were observed on SEM micrograph for the damaged sample. A 60% reduction of PL intensity was also detected by photoluminescence measurements. These results rule out such a possibility. We concluded 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 favors the formation of low resistance ohmic contacts, consistent with contact resistance measurements. We believe that the mechanism involving the incorporation of impurities onto the surface of GaN, giving rise to a nonradiative recombination level which increases the recombination velocity. XPS measurements identified traces of Cl (the plasma chemistry being Cl₂ and BCl₃), 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

Even during bombardment at liquid nitrogen temperatures, GaN is quite resistant to ion disordering due to efficient defect relaxation processes. However, defect disordering is not perfect and residual disorder accumulates as a function of increasing ion dose, often with preferential disordering at the surface. 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 Raman scattering and x-ray reflectivity, 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 in the ion dose increases. This surface disordering and associated process under ion bombardment does not appear to be very sensitive to implantation temperatures up to a few hundred degrees Celsius. Capping of GaN with SiO₂ or SiN₄ layers prior to ion bombardment does not eliminate surface disordering and N loss. Indeed, for Au ions 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


11:45 AM T7.10
DIODE FABRICATION WITH HIGH DOSE Mg⁺ ION IMPLANTATION INTO n-GaN. Leonid Krammok, Agija Savkunov, Implant Sciences, Wakefield, MA, Lionel Beuthellite, Kenneth Vaiace, Sensors Directorate, FBL, Hanscom AFB, Bedford, MA; Najy El Khayat, Solid State Microelectronics Research Group, University of Guelph, Guelph, ON, Canada; D. Novak, 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 anneal more effectively in interaction with each other, with dislocations, and with crystal grain boundaries. The impurity solubility in GaN increases as the temperature rises. N-type GaN grown on Al₂O₃ or SiC with a conductive buffer layer, was implanted by Mg⁺ ions with doses of 5x10¹⁵, 5x10¹⁶, and 5x10¹⁷ cm⁻² at implant temperatures of 800-1000°C. All implants were done through AlN or metal capillary films. Before and after implantation, and after annealing at 1100-1200°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 LV characteristics and LED wavelength spectra vs. direct current through the p-n junction. The comparison of Mg⁺ implanted p-n junctions with vertical diode structures grown by MOCVD is presented and discussed.
1300 PM T8.3 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 some of the dopants and silicon preferentially evaporate. This causes the SiC surface to roughen and the electrical properties of the underlying SiC to change. Consequently, the formation of point defects such as silicon vacancies, AIs can prevent these problems up to annealing temperatures of 1600°C at which point, #, begins to evaporate. Graphite caps do not prevent the evaporation and activation but only when this evaporation is low and it crystallizes at temperatures >1600°C and can only be removed by ion beam milling. However, when used in conjunction with the AIS in an AIS 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.


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 interface characteristics of Ni ohmic contacts we have developed a Ni based composite contact to n-SiC, Ni/W/Si/Ti/Pt. The material properties of the Ni-deposited and annealed Ni/W/Si/Ti/Pt composite contact metallization to 4H n-SiC were quantitively assessed via AFM, FESEM, AES, RBS, TEM and wafer stress measurements. Additionally, using this type of composite contact, low voltage, low current metal-SiC metallization in response to pulsed high power switching, i.e., the in device service operational envirionment, was assessed via acute pulsed thermal fatigue testing. Our results demonstrated that ohmic contact formation was achieved via RFA 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 composite-SiC interface suffered minimal degradation after exposure to pulsed thermal fatigue testing. Details of the aspects of contact formation and the results of the pulsed thermal fatigue testing will be presented and discussed.

2330 PM T8.3 STABLE Ti/TiSi2/Pt OHMIC CONTACT ON N-TYPE 6H-SiC EPIPLATER AT 600°C. Robert S. Okoje, NASA Glenn Research Center, Instrumentation and Control 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. In this work, we determine the appropriate metallization schemes required to support long-term device operation at high temperatures up to 600°C. An advantage of the high temperatures is that the contact resistance is significantly lower than at room temperature. In this study, the contact was the Ti/TiSi2/Pt, with the n-type 6H-SiC epilayer tested in atmosphere at 600°C. This work is in response to an effort to develop ohmic contacts to n-type 6H-SiC epitaxial material. 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 high-temperature storage. Contact resistivity in the range of factors of 10^-11 to 10^-12 ohm 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 drastic changes at the interfacial reaction zones. The intrusion of oxygen from the environment is observed to be successfully arrested using nitrogen as an atmosphere during the Ti/TiSi2/Pt contact deposition. The Pt is an effective adhesion layer for the Ti/TiSi2 contact to n-SiC.
obtained by RBS measurements, assuming Vegard linear law. Our current research is focused on the effects of ion implantation as well as the microstructural 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 investigations on the electrical properties of SiC:Ge alloys processed from annealing over an extended temperature range. We will report on the effect of Ge on the optical transmission, Raman spectra, and the electrical conductivity.

3:45 PM T8.6
CHARACTERIZATION OF n-TYPE LAYER BY 2° ION IMPLANTED IN 4H-SiC. Yasunori Tanaka1,2, Naoto Kobayashi1,2, Hajime Okumura1,2, Masahiko Nisimura1,2, Masaaki Iwagawa1, Masahiko Ogura1,2, Hideo Tanoue1, and Kazuo Arai1,2
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For n-type doping 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(100) wafers with epi-layer-type, p=1-10X10^15/cm^2, Si-face,10μm) purchased from Cree Research Inc. To make up the S-implanted layer as a box profile we carried out the multiple beam implantation in the energy range of 40-100keV with the total dose of 5.0X10^{15} /cm^2 at 500°C. The implanted samples were annealed in the furnace at 1000°C for 20 minutes in Ar ambient for the electrical characteristic measurements. Hall effect measurements were carried out to investigate the electrical property. For 5.0X10^{15} /cm^2 dose we estimated the impurity level from conductivity band at ~15050cm. This value is relative deeper than that of nitrogen.

For more higher dose, 1.0X10^{15} /cm^2, we estimated it to ~1200cm.

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. Chang, C.C. Tin, J.H. Won and J.R. Williams, Physics Department, Auburn University, AL; K. McDonald1, K. McDonald, R.A. Weil2, M. Di Ventra1, S.T. Pantelides1 and L.C. Feldman1

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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 properties of SiC is its wide energy gap (∼3 eV). Other wide energy gap semiconductors (the group III nitrides and diamond) have been realized as a result of the high quality SiC substrate and the high purity SiC epitaxial layers. However, SiC is a wide bandgap semiconductor used in high-voltage and high-temperature devices. SiC has a high breakdown electric field and a high thermal conductivity. SiC has been shown to be a promising candidate for high-temperature and high-power applications. In this study, we investigated the effects of post-growth annealing conditions on the interface state density and the inversion channel mobility for SiC MOSFETs.

The interface state density in the gate region can be reduced by using a high-temperature annealing process. However, the high-temperature annealing process can result in a decrease in the inversion channel mobility. To investigate these effects, we used a combination of high-temperature annealing and a low-temperature annealing process. The high-temperature annealing process was performed at 900°C for 30 minutes, while the low-temperature annealing process was performed at 200°C for 30 minutes. The interface state density was measured using a high-field mobility measurement technique. The inversion channel mobility was measured using a low-field mobility measurement technique.

5:00 PM T8.8
EFFECTS OF ELECTRODE SPACING ON REACTIVE ION ETCHING OF 4H-SiC. J. Bonds, G.E. Carter, J.B. Cassidy, Mississippi State University, Materials Research Laboratory, Electrical and Computer Engineering Department, Starkville, MS; J.D. Scofield, U.S. Army 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 is monolithic microwave integrated circuits (MMICs) and microelectromechanical systems (MEMS) is through the use of dry (or plasma) etching [1]. Of the dry etch techniques available, reactive ion etching (RIE) is the low pressure etch technique of choice. In this paper, we will discuss the effects of varying the etching techniques on the 4H-SiC etch rate using RIE. The etch rate variation in 4H-SiC is affected by various factors such as the etch gas mixture, the chamber pressure, and the substrate temperature. In this study, we varied the etch gas mixture, the chamber pressure, and the substrate temperature to investigate their effects on the etch rate. The results show that the etch rate varies significantly with the above factors. For example, the etch rate increases with increasing chamber pressure and substrate temperature. The etch rate is also affected by the etch gas mixture. For a given chamber pressure and substrate temperature, the etch rate decreases with increasing etch gas mixture. These results are in agreement with previous studies and provide useful information for the design of etch processes for 4H-SiC.
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.