SYMPOSIUM G

GaN and Related Alloys

November 26 – December 1, 2000

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TUTORIAL

FT G: MATERIAL CHARACTERISTICS OF THE III-NITRIDES
Sunday, November 26, 2000
2:00 p.m. - 5:00 p.m.
Room 203 (Hynes)

Our understanding of the properties of the III-nitrides continues to grow at a rapid rate due to the worldwide interest in developing these materials for semiconductor device applications. This interest has resulted in systematic efforts to synthesize bulk materials and to characterize their mechanical and electronic properties. The last few years have seen a much better understanding of the band structure, defect structures, thermal expansion coefficients, non-linear optical coefficients, piezo-electric, pyroelectric, thermal conductivity and other important properties that are needed for manufacturing devices and understanding their performance. This tutorial will bring together the latest information on these topics. Substantial new efforts have been made to produce bulk crystals of the III-nitrides that have allowed much more thorough material characterization to be carried out. The tutorial will also include some discussion of what controversies remain.

Instructions:
Michael S. Shur, Rensselaer Polytechnic Institute
Leo J. Schowalter, Rensselaer Polytechnic Institute

SESSION G1: ADVANCES IN GROWTH
Chairs: Hiroshi Amano and Akira Usui
Monday Morning, November 27, 2000
Room 210 (Hynes)

8:30 AM *G1.1
THE CHEMISTRY OF GALLIUM NITRIDE GROWTH.
T.F. Kuech, Ramchandra Watwe, Ling Zhang, Jingxi Sun, and J.A. Dumesic, University of Wisconsin-Madison, Department of Chemical Engineering, Madison, WI; J.M. Redwing, Dept. of Materials Science, Pennsylvania State University, University Park, PA.

The metalorganic vapor phase epitaxy of GaN is complicated by the extensive and pervasive complex gas phase chemistry within the growth system not typically found in the metal organic vapor phase epitaxy of other III-V materials. This gas phase chemistry leads to the high sensitivity of the material properties on the detailed fluid dynamics within the system. The most well known reaction is the formation of a gas phase adduct between trimethyl gallium, $(CH_3)_3Ga$, and ammonia, NH_3, that readily leads to the formation of more complex gas phase products, such as $((CH_3)GaNH_2)_x$=2 or 3, which further react and complicate the detailed growth behavior. The presence of other gas phase nitrogen compounds can modify these reactions. The growth of GaN and related materials is complicated by gas phase reactions. For example, the addition of trimethyl amine to the gas phase, $(CH_3)_3N$, can lead to a suppression of this rapid adduct formation and oligomerization, thereby in principle simplifying the growth behavior and reactor design. Trimethylamine and trimethyl gallium in hydrogen do not participate in such high temperature reactions. The pyrolysis of $(CH_3)_3Ga$ and $(CH_3)_3N$, when combined, appear to follow independent decomposition pathways. The detailed mechanisms responsible for the observed gas phase reactions were investigated by density functional theory (DFT) calculations. These calculations initially determined the heat of reaction for the overall reaction as well as the elementary steps. We have combined these computational efforts with experimental reaction studies to develop a model of the growth environment present in the reactor. Computational fluid dynamics (CFD) based reactor modeling, combined with gas phase kinetics studies, was used to determine the transport and reaction behavior within a high performance vertical MOVPE reactor. The complexity of the growth chemistry model was increased in a step-wise fashion. At each step, the concentration profiles were determined using available recent kinetic data. The correlation with experimental reactor data was carried out provided insight into the critical parameters requiring control in order to achieve uniform materials properties and growth rates.

9:00 AM G1.2
SILICON AT (0001)GaN SURFACES: SURFACE STRUCTURES AND ADATOM KINETICS. A.L. Rosa, J. Neugebauer, Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, GERMANY; J.E. Northrup, Xerox Palo Alto Research Center, Palo Alto, CA; Chae-Deok Lee, R.M. Feenstra, Department of Physics, Carnegie Mellon University, Pittsburgh, PA.

Recent experiments [1] have shown that Si has a strong effect on the morphology of GaN surfaces: small amounts of Si on GaN modify the growth from step-flow to 3D-growth giving rise to the formation of quantum dots (QD). However, it is not yet clear whether it is the Si alone or the combination of Si with H which leads to this behaviour. We have therefore combined scanning tunneling microscopy (STM) and first-principles calculations to systematically study the adsorption of Si at (0001)GaN surfaces. We have determined the most stable Si-induced surface reconstructions as a function of the atomic chemical potentials. Under N-rich conditions the thermodynamically stable structure is a 2x2 reconstruction with two N adatoms residing on a full monolayer of Si. Under more Ga-rich conditions we find that Si is incorporated in subsurface sites. In particular we find that a 2x2 structure consisting of a Ga adatom on a monolayer of 3Ga 1 Si with a Si_{Ga} atom in the third layer is very stable. This result is consistent with the STM investigations where a 2x2 adatom structure is observed. Analysing these structures we find that stable surfaces tend to maximize the number of Si-N bonds at the expense of Si-Ga bonds. Based on the calculated equilibrium surface structures we have studied the migration paths and diffusion barriers of Ga and N adatoms. We find that Ga has a much higher mobility than N, similar to what has been calculated for the bare (0001)GaN surface. On the basis of these calculations we will discuss the effect that Si has on the growth of GaN.
[1] S. Tanaka *et al.*, Appl. Phys. Lett. 69, 4096(1996).

9:15 AM G1.3
DRASTIC REDUCTION OF THREDING DISLOCATION DENSITY OF AlGaN ON SiC BY USING HIGHLY-Si-INCORPORATED AlGaN SUPERLATTICE. Makoto Ainoya[1,2], Hideki Hirayama[1], Atsuhiro Kinoshita[1,2], Akira Hirata[2], Yoshinobu Aoyagi[1]. [1]The Institute of Physical and Chemical Research (RIKEN), Saitama, JAPAN; [2]Dept of Chemical Engineering, Waseda Univ, Tokyo, JAPAN.

A new in-situ technique to reduce threading dislocation density (TDD) on AlGaN buffers within sub-microns growth is demonstrated. To date, some methods to reduce TDD such as ELO and Pendeo-epitaxy were reported. These methods need complicated processes and several-microns growth to make the surface flat. However, in order to prevent cracks, it is necessary to reduce the dislocation density within sub-micron growth, especially on SiC substrate. In this report, we achieved to decrease TDD on AlGaN buffers by using highly-Si-incorporated AlGaN SLs. This technique is exactly in-situ process and the surface is kept flat throughout the total growth. We achieved two-orders of magnitude smaller TDD than a sample without the SLs with 0.8 μm-thick growth. The samples were fabricated on SiC(0001) substrate by metal-organic-vapor-phase epitaxy (MOVPE). Thin AlN film and 200 nm-thick undoped $Al_{0.15}Ga_{0.75}N$ buffer were grown at first. Then, six periods of SLs consisting of 20 nm-thick highly-Si-incorporated $Al_{0.15}Ga_{0.75}N$ and 80 nm-thick undoped $Al_{0.15}Ga_{0.75}N$ layers were grown. Lastly 100 nm-thick $In_{0.2}Ga_{0.8}N$ layer was grown to count TDD on the AlGaN surface. We estimated Si composition is up to over 1%. TDD on AlGaN with and without Si-incorporated SLs were $1\sim2\times10^8$ cm^{-2} and 2×10^{10} cm^{-2}, respectively. We also obtained similar effects on Al_2O_3 substrate.

9:30 AM G1.4
MECHANISMS OF DISLOCATION TERMINATION IN GaN THIN FILMS BY ANTI-SURFACTANT MEDIATED EPITAXY.
Satoru Tanaka, Research Institute for Electronic Science, Hokkaido University, Sapporo, JAPAN; Misaichi Takeuchi Hideki Hirayama, Yoshinobu Aoyagi, The Institute of Physical and Chemical Research (RIKEN), Wako, JAPAN.

We have previously demonstrated GaN quantum dot (QD) formation on pseudo-lattice matched AlGaN surfaces by the use of Si anti-surfactant [1]. Ordinal step-flow growth is changed to three-dimensional growth mode with the supply of Si atoms on AlGaN surfaces and thus this induces quantum dot formation. The detailed study on the mechanisms indicated Si-N masks with nano-meter order scale are responsible for the QD formation. Through the investigation we recently found that threading dislocations (TDs), which were formed in GaN buffer layers on AlN/6H-SiC(0001) substrates, were effectively terminated at the anti-surfactant treated interface, resulting in drastic reduction (factor of 10^{-3}) of the dislocation density in GaN over-layers [2]. Experimental procedures were similar to those for QD formation except for the growth of GaN buffer layer on AlN/6H-SiC(0001) substrates and the Si feeding amount. After depositing a $\sim$0.5 micron-thick GaN film (GaN buffer-layer) TESi ($\sim$96 nmol) with a H2 carrier gas was introduced to the surface. In this process a Si-N layer with sub-monolayer coverage (Si-N mask) was achieved. Finally, an approximately 2 micron-thick GaN film (GaN over-layer) was grown on this surface. Cross-sectional TEM observation showed that most TDs were diminished at the GaN over layer/GaN buffer layer interface by forming dislocation loops. The

TDs were terminated by the Si-N masks, where no GaN nucleation was kinetically possible as was seen in GaN QD formation. GaN overgrowth on Si-N masked regions resulted in the termination of TDs and the formation of a new type of dislocations which extended along the interface. Such dislocations along the interface reacted with another TDs to create dislocation loops. The detailed mechanisms of TD termination will be presented based on conventional and high-resolution TEM observation. [1] S. Tanaka et al., Appl. Phys. Lett. 69, 4096 (1996). [2] M. Takeuchi et al., in this symposium.

10:15 AM *G1.5
ROLE OF HYDROGEN IN SURFACE RECONSTRUCTIONS AND GROWTH OF GaN. Chris G. Van de Walle, Xerox PARC, Palo Alto, CA; Jörg Neugebauer, Fritz-Haber-Institut, Berlin, GERMANY.

A detailed understanding of surface reconstructions on nitride semiconductors is essential for improved control over growth and materials properties. Previous studies have focused on surface reconstructions of *bare* GaN surfaces. Here we examine the role of hydrogen. Hydrogen is abundantly present during metal-organic chemical vapor deposition (MOCVD), the most commonly used growth technique for nitrides. Hydrogen has been introduced also in molecular-beam epitaxy (MBE), either directly or through growth with an NH_3 source. We address these issues through a detailed investigation of hydrogen interactions with GaN (0001) surfaces, based on pseudopotential-density-functional calculations. We will outline the theoretical approach for studying the stability of various surface reconstructions as a function of stoichiometry (Ga-rich *vs.* N-rich conditions), as well as of the hydrogen chemical potential, with the latter exhibiting a significant temperature dependence. Our studies indicate that the energetically most favorable structures are those in which "electron counting" is satisfied, i.e., in which no empty N dangling bonds nor filled Ga dangling bonds occur. Under N-rich conditions, reconstructions maximizing the number of N-H bonds are favored, due to the large N-H bond strength. These include structures in which a nitrogen atom is bonded to a surface Ga atom in an on-top position, as well as to two or three H atoms – a configuration directly related to adsorption of NH_2 or NH_3. Under Ga-rich conditions, we find a variety of competing 2x2 reconstructions, whose stability sensitively depends on the hydrogen chemical potential. At MOCVD growth temperatures the H-covered surfaces are only marginally stable. The stability of the H-covered surfaces increases at lower growth temperatures (including those used in MBE growth and in MOCVD growth of InGaN alloys). We will discuss how these investigations provide insight into the regions of stability for GaN and InGaN growth.
CVdW thanks the Fritz-Haber-Institut and Paul-Drude-Institut, Berlin, for their hospitality.

10:45 AM G1.6
REVERSIBLE HYDROGEN RELEASE AND DOPANT ACTIVATION IN GALLIUM NITRIDE: EXPERIMENT AND THEORY. S.M. Myers, A.F. Wright, G.A. Petersen, W.R. Wampler, C.H. Seager, M.H. Crawford, J. Han, Sandia National Laboratories, Albuquerque, NM.

The release of hydrogen during isothermal annealing and the associated activation of dopants were experimentally investigated for Mg-doped, MOCVD GaN at temperatures from 700 to 1000°C and anneal times from 7 seconds to 65 hours. Hydrogen uptake from the gas phase and the resultant dopant repassivation were measured at 500 to 800°C. Use of the deuterium (D) isotope allowed profiling by nuclear-reaction analysis, and this was accompanied by measurements of resistivity, Hall effect, and IR absorption by the Mg-D center. These experimental results and others from the literature were described by a unified theoretical model with two adjustable parameters. In the model, density-functional theory was employed to calculate formation energies, vibration frequencies, and diffusion activation energies for H, H0, H-, interstitial H2, and the neutral Mg-H complex. This information was then incorporated into a diffusion-reaction formalism to describe H behavior at elevated temperatures. Our experiments indicate a strong surface barrier to H release, and this effect was provisionally treated using a simplified physical picture wherein equilibration between solution and surface sites is rapid and recombinative desorption is rate-determining. Our experimental and theoretical studies are currently being extended to n-type GaN containing Si and O donors; in this case, density functional theory predicts neutral dopant-H complexes somewhat less stable than the Mg-H center, and initial solubility results conform well to model predictions. Additionally, the theoretical treatment of H behavior is being generalized to encompass space-charge effects in the vicinity of device junctions. Progress in these ongoing studies will also be reported. Supported by the US Dept. of Energy, Office of Basic Energy Sciences, under Contract DE-AC04-94AL85000.

11:00 AM G1.7
THERMODYNAMICS VERSUS KINETICS IN THE GROWTH OF GaN/AlN QUANTUM DOTS BY MOLECULAR BEAM EPITAXY. Bruno Daudin, Guido Mula, Alain Bourret, Guy Feuillet, Nikos T. Pelekanos, Christoph Adelmann, Julia Simon, CEA-Grenoble, Département de Recherche Fondamentale sur la Matiëre Condensée, Grenoble, FRANCE.

GaN/AlN quantum dots (QD) grown by plasma-assisted molecular beam epitaxy are appealing because of the possibility of a large emission wavelength modulation by changing the size of the dots. This is specially true in the case of the hexagonal phase, due to the presence of a huge internal electric field. Although being of major importance for practical devices, the control of the GaN dot size distribution is still a major issue, due to the lack of a full understanding of the formation mechanism. We adress this point by presenting here a complete study of the formation of the QDs as a function of several parameters, namely the Ga/N ratio, the growth temperature and the maximum GaN growth rate. The experimental techniques were Reflection high energy electron diffraction (RHEED), AFM and Photoluminescence. The main result is the evidence of a continuous change from a 3D (rough) to a 2D/3D (Stranski-Krastanow) and to a 2D (flat) growth front by increasing the Ga/N ratio or decreasing the growth temperature. Furthermore, it has been demonstrated that, for a Ga flux high enough, a Ga film is present on the AlN surface from the very first stages of the GaN growth. The nature of the growth has been found to be correlated to the presence of the Ga film which drastically influences the mobility of the adatoms. Along this view, the results are consistently interpreted by assuming that the GaN growth mode as well as the strain relaxation mechanism results from a competition between thermodynamics and kinetics. In high (low) Ga/N flux ratio conditions, the growth mode is 2D (Stranski-Krastanow) and the strain relaxation is plastic (elastic). On these basis, a new method to grow GaN QDs is presented, in which the AlN surface is first exposed to Ga and next to the N plasma.

11:15 AM G1.8
GROWTH AND OPTICAL PROPERTIES OF GaN QUANTUM DOTS EMBEDDED IN Al_2O_3 MATRICES. C.W. Teng, J.F. Muth, R.M. Kolbas, North Carolina State University, Department of Electrical and Computer Engineering, Raleigh, NC; A.K. Sharma, A. Kvit, J. Narayan, North Carolina State University, Department of Materials Science and Engineering, Raleigh, NC.

GaN quantum dots are of great interest for their fundamental physical properties and potential applications in optoelectronic devices. In the present report, five alternating layers of crystalline GaN quantum dots embedded in an amorphous Al_2O_3 matrix were deposited on sapphire (0001) substrates by pulsed laser deposition. The structural properties were investigated by high-resolution transmission electron microscopy and atomic force microscopy. The photoluminescence (PL) spectra were excited by the third harmonic output of a mode-locked Ti:sapphire tunable laser (~270 nm). A room temperature PL peak was observed at ~332 nm, about 0.32 eV blue shifted relative to the band gap of bulk GaN. Very little yellow emission was detected. This blue shift is shown not matrix-related by measuring PL on similar structures without quantum dots. The amorphous nature of the matrix also sidesteps the piezoelectric effect on the emission energy of GaN nanostructures. Experimental data will be presented to demonstrate the physical origin and potential device applications of the blue-shifted luminescence peak from the nanostructures.

11:30 AM G1.9
STRUCTURE AND OPTICAL PROPERTIES OF GaN BULK CRYSTALS GROWN FROM THE LIQUID PHASE. M. Albrecht M. Nerding, and H.P. Strunk, Universitaet Erlangen-Nuernberg, Institut für Werkstoffwissenschaften, Mikrocharakterisierung, Erlangen, GERMANY; V.A. Ivantsov, V. Sukhoveev, and V.A. Dmitriev, PhysTech WBG Research Group, Ioffe Institute, St.-Petersburg, RUSSIA, TDI, Inc., Gaithersburg, MD.

Dislocation-free GaN single crystalline materials are ideal substrates for group III-nitride devices. Today three different approaches exist to realise such structures (i) growth from solution at high temperatures and high pressure, (ii) lateral epitaxial over growth, and (iii) growth of thick layers on a foreign substrate and subsequent removal of the substrate. Despite the success of these methods with respect to dislocation reduction (<102 cm^{-2} in case of solution growth, around 10^6 cm^{-2} in case of epitaxial techniques) all of them result in individual substrates. No large bulk single crystals have been realised up to now. We present results on structural and optical properties of GaN crystals grown from liquid phase at 1000°C and at pressures lower then 2 atm. The crystals are grown from Ga-based melt in a nitrogen containing atmosphere. The potential of this method to grow single crystals with high optical and structural quality can be shown for small crystals that nucleate spontaneously in the melt. These crystals are hexagonal platelets with a size of 4x4x0.1 mm. Apart from nanopipes and single inversion domain boundaries no extended defects can be revealed by transmission electron microscopy. We

analyse the single crystalline nature of these crystallites by electron backscattering pattern in the scanning electron microscope. Real bulk material can be obtained from seeded growth (various seeds are used) from the solution. We obtain GaN ingots with a length of 15 mm and a diameter of 20 mm, which can be sliced into wafers. These wafers show predominant (0001) orientated regions with a size up to 3x1.5 mm, that are surrounded by regions with high densities of stacking faults and cubic inclusions. The dislocation densities are in the range of $10^7 cm^{-2}$ within the well oriented parts of the wafer.

11:45 AM G1.10
GROWTH OF SELF-SEEDED ALUMINUM NITRIDE BY SUBLIMATION-RECONDENSATION AND SUBSTRATE PREPARATION. J. Carlos Rojo, Glen A. Slack, Ken Morgan, Leo J. Schowalter, Crystal IS, Inc., Latham, NY; Nikolai L. Yakovlev, Yuriy Shusterman, Physics, Applied Physics and Astronomy Dept., Rensselaer Polytechnic Institute, Troy, NY.

Aluminum nitride (AlN) has received attention as a candidate for III-nitride epitaxy applications due to its close lattice match, minimal differential thermal expansion to GaN, and high thermal conductivity. The scale-up of the AlN sublimation-recondensation growth, first demonstrated by G. Slack, provides a good prospect to this technique in producing cost-efficient, commercial AlN substrates. There is interest on producing AlN substrates, not only as a competing substrate to grow GaN, but also as a more desirable substrate for devices with Al-rich nitride epitaxial layers. Large (up to 14mm diameter) aluminum nitride (AlN) boules have been grown by the sublimation-recondensation method to study the preparation of high-quality single crystal substrates. Substrates of more than $1cm^2$ in area have been obtained with a very low density of low-angle grain boundaries. Our studies have demonstrated the possibility of preparing those substrates for epitaxial growth using chemical-mechanical polishing (CMP) techniques although significant differences between the different crystallographic orientations have been observed. To produce these AlN boules, a self-seeded technique is currently being used. Therefore, the quality and size of the resulting single crystal grains in those boules are critically related to the nucleation conditions during the early stages of the growth process. The location of the nuclei during the growth process is strongly affected by the temperature distribution along the crucible walls. In addition, the differential growth rate along different crystallographic orientations significantly influences the quality, number of grains, and their crystallographic orientation respect to the crucible axis. Also, the coloration of the growing grains can vary from colorless to different orange-brown tones. Even though there are not conclusive studies on its origin, our results indicate that this latter phenomenon could be related to the quality of the starting material and the absolute growth temperature during the process.

SESSION G2: ADVANCED ALLOYS AND CHARACTERIZATION
Chairs: Thomas F. Kuech and Alan F. Wright
Monday Afternoon, November 27, 2000
Room 210 (Hynes)

1:30 PM *G2.1
MOVPE GROWTH AND OPTICAL CHARACTERIZATION OF GaAsN ALLOYS. Kentaro Onabe, Daiichiro Aoki, Jun Wu, Univ of Tokyo, Dept of Applied Physics, Tokyo, JAPAN; Hiroyuki Yaguchi, Saitama Univ, Dept of Electrical and Electronic Systems, Saitama, JAPAN; Yasuhiro Shiraki, Univ of Tokyo, RCAST, Tokyo, JAPAN.

Due to a huge band-gap bowing, the GaAsN alloy is expected as a narrower-band-gap material for the heterostructure with GaAs, giving a conduction-band discontinuity larger than 300meV. In our study, high-quality luminescent GaAsN films have been obtained with the N concentrations up to 3.1% by MOVPE using trimethylgallium, AsH3 and 1,1-dimethylhydrazine as precursors. The X-ray rocking curve for the (400) diffraction showed a single-peak nature of the GaAsN films. The grown film surfaces were mirror-like but with a cross-hatch pattern for the N concentrations higher than 2% due to the large lattice-mismatch (>0.5%). Low-temperature (20K) photo-luminescence (PL) properties are excellent for all the samples (N=0.43%~3.1%) with a single near-band-edge emission peak without the defect-related deep-level luminescence often found in the previous reports. The near-band-edge emission survives even at room temperature with a significant intensity. From the red-shift behavior of the PL peak, the band-gap bowing parameter was estimated. It is found that the bowing parameter is dependent on the N concentration; 24.0eV for N<1% and 17.0eV for N>1% at 20K, and 22.4eV for N<1% and 14.5eV for N>1% at room temperature. These values are consistent with the data from optical absorption measurements. The decrease of the PL intensity is rapid with rising temperature up to ~100K, much like the emission associated with the N isoelectronic traps in GaAs. Then, the PL intensity decrease tends to much slower one up to 300K, like the emission associated with the free-electron band. The PL peak energy shift shows a similar activation feature with temperature. Such localization nature of the band-edge states is considered as essential in GaAsN alloys as far as the N concentration up to a few percent is concerned. We have also found by spectroscopic ellipsometry that the N incorporation considerably affects not only the band-edge states but also higher energy bandgaps.

2:00 PM G2.2
NITRIDE-RICH HEXAGONAL GaNP GROWTH USING METALORGANIC CHEMICAL VAPOR DEPOSITION. S. Yoshida, Y. Ito, and J. Kikawa, Yokohama R&D Laboratories, The Furukawa Electric Co., Ltd, Yokohama, JAPAN.

III-V-N compound semiconductors, such as GaNP, are very attractive for light-emitting diodes with a wider visible wavelength due to gigantic band-gap bowling. There has been no report concerning the optical property in the region of violet or blue emission of $GaN_{1-x}P_x$ growth using metalorganic chemical vapor deposition (MOCVD). In this paper the growth of GaNP using laser-assisted MOCVD is reported. In this method, we used an Ar-F laser in order to decompose source gases at lower temperature. Trimethylgallium (TMG), ammonia (NH_3), and tertialybuthylphosphine (TBP) were used for the growth. The growth temperatures were 1000°C-850°C. After growth, annealing was carried out at 1000°C-850°C for improving the crystal quality.
As a result, N-rich $GaN_{1-x}P_x$ could be grown at 800°C-950°C. The surface morphologies of $GaN_{1-x}P_x$ were improved when the growth temperature was increased to above 900°C. Using an analysis of secondary ion mass spectrometry (SIMS) and X-ray diffraction, we confirmed that P was incorporated into GaN. Furthermore, we investigated the photoluminescence of $GaN_{1-x}P_x$ at r.t., 77K, and 5K. A band-edge emission (382 nm) of $GaN_{1-x}P_x$ was observed at 77K. This peak was shifted to 25nm compared with the GaN band-edge emission. The composition ratio, x, of $GaN_{1-x}P_x$ corresponded to be about 1%. This value of the GaNP peak shift is larger compared with previous reported values when grown by MOCVD. It is suggested that $GaN_{1-x}P_x$ can be expected for materials for a blue-violet LED.

2:15 PM G2.3
GaAsN vs. BGaAs ALLOYS: SYMMETRY-INDUCED DIFFERENCES. N. Gonzalez Szwacki and P. Boguslawski, Instytut Fizyki PAN, Warsaw, POLAND.

Incorporation of 1 atomic percent of nitrogen into GaAs reduces its band gap by as much as 0.15 eV. For this reason, $GaAs_{1-x}N_x$ alloys with $0.01<x<0.03$ are receiving a considerable attention due to their potential optonic applications in the infrared regime. Experiment also shows a strong reduction of the pressure coefficient of the band gap of $GaAs_{1-x}N_x$ compared with GaAs. On the other hand, a comparable amount of boron in GaAs induces much smaller changes of the band gap, and a much weaker anomaly of the pressure coefficient. This difference is surprising given the fact that B, like N, is also from the second row of the Periodic Table. To understand these findings we have performed first-principles calculations of the electronic structure of $GaAs_{0.97}N_{0.03}$ and $B_{0.03}Ga_{0.97}As$. In agreement with experiment we obtain that the presence of N strongly reduces both the band gap and its pressure coefficient. The boron-induced effects are much less pronounced. This difference is explained based on the group theory and the analysis of wavefunctions of the conduction bands as follows. The impurity potential couples the bottom of the conduction band with the secondary minima from the X point of the Brillouin Zone. However, in the case of the N:As substituting anion there is a strong coupling with the lowest minimum at X, explaining the observed pressure anomalies. In contrast, in the case of the B:Ga substituting cation this coupling is forbidden by symmetry. The symmetry-allowed coupling occurs with the higher-energy state at X, but it is weaker, and thus the effects of B are weaker. Moreover, a transition from the direct to the indirect band gap at about 6 GPa is predicted.

2:30 PM G2.4
ELECTRONIC STRUCTURE OF GaAsN AND GaPN ALLOYS. Paul Kent, Alex Zunger, National Renewable Energy Laboratory, Golden, CO.

It is well known that the incorporation of nitrogen in GaP and GaAs results in a strong band gap bowing, however the mechanisms for this effect are not well understood. Using large supercell empirical pseudopotential calculations, we have investigated the electronic and optoelectronic properties of GaPN and GaAsN as a function of nitrogen concentration. In contrast to phenomenological models and earlier supercell calculations, our calculations reveal a strong multiband coupling, and a non-trivial dependence on the positions of neighboring impurities. We analyze the structure and evolution of the alloy conduction band in terms of localized states arising from

isolated nitrogen atoms, nitrogen pairs, extended clusters, and their mutual interactions. At low nitrogen concentrations, gap states result from nitrogen pairs, but with increasing nitrogen concentrations these states are swept away by the conduction band minimum as it moves to lower energies. Our calculations show that the detailed structure of the conduction band is very sensitive to nitrogen clustering, and the evolution of the conduction band minimum cannot be accurately described by a simple anti-crossing model.

2:45 PM G2.5
COMPREHENSIVE STUDY OF ANOMALOUS CONDUCTION BAND STRUCTURE OF InGaAsN. C. Skierbiszewski, P. Perlin, P. Wisniewski, T. Suski, High Pressure Research Center "Unipress" Warsaw, POLAND; J. Geisz, National Renewable Energy Laboratory, Golden, CO; W. Jantsch, Institut für Halbleiterphysik, Johannes-Kepler-Universität, Linz, AUSTRIA; D. Mars, Agilent Laboratories, Palo Alto, CA.

GaAsN is a new class of semiconductor characterized by an unexpected and large energy gap reduction with an increasing nitrogen content in GaAs. The use of quaternary InGaAsN alloy gives a unique possibility of semiconductor band engineering while preserving lattice match to GaAs substrate. InGaAsN, even for Nitrogen content not exceeding 0.02, is a material strikingly different from GaAs and GaN. This is why this compound requires a description beyond the virtual crystal approximation which is so useful in case of alloys like AlGaAs. All existing theoretical model of InGaAsN predict that interaction between Nitrogen states and conduction band of the matrix leads to serious reorganization (or even splitting) of the latter band. In this paper we will focus on the experimental study of conduction band anomalies observed in this unusual alloy. By means of optical absorption experiment performed on free standing layers of InGaAsN we succeeded for the first time to get an experimental insight into the shape of conduction band DOS function in the broad energy and temperature ranges (0.8-2.5eV; 10-300 K). By comparing electrical Hall experiment and infrared reflectivity for differently doped samples we were able to deduce the density of states, conduction band electrons effective mass [1] and the conduction band dispersions. The electron effective mass few times larger than that corresponding to GaAs with the same electron concentration is found. Accordingly, dispersion relations show extremely high degree of nonparabolicity present in the conduction band. These findings provide us with an opportunity to discuss the applicability of Shan-Walukiewicz band anticrossing model [2], proving predictivity of this simple approach. Last, we will discuss the problem of n-type doping of this material focusing on the Se donors in InGaAsN and their behavior under hydrostatic pressure. In this context some metastable effects resembling DX-like center behavior will be analyzed. [1] C. Skierbiszewski et al. Appl. Phys. Lett, 76, 2409, (2000) [2] Shan, Walukiewicz et al. Phys. Rev. Lett. 82, 1221, (1999)

3:30 PM G2.6
SPONTANEOUS FORMATION OF INDIUM-RICH NANO-STRUCTURES ON InGaN(0001) SURFACES. Huajie Chen, R.M. Feenstra, Dept Physics, Carnegie Mellon University, Pittsburgh, PA; J.E. Northrup, Xerox PARC, Palo Alto, CA; T. Zywietz and J. Neugebauer, Fritz-Haber-Institut der MPG, Berlin, GERMANY.

InGaN(0001) surfaces prepared by molecular beam epitaxy have been studied using scanning tunneling microscopy and first principles total energy calculations. Strong surface segregation of the indium is found, with In atoms forming a monolayer at the surface and also partially occupying second layer sites (substituting for Ga). We observe that an array of surface pits, which we refer to as vacancy islands, forms to relieve the strain produced by the second layer In occupation. The pits consist of missing first layer In atoms and missing third layer N atoms. Moreover, we find that it is energetically favorable for In atoms to laterally segregate to the edges and interior of the vacancy islands, to sites where they form only 0, 1 or 2 bonds with N atoms compared to 4 bonds for bulk incorporation or 3 bonds for incorporation in sites on the (0001) growth surface. This lateral segregation results in a higher In concentration in and at the edges of the vacancy islands, thus giving rise to In compositional fluctuations at the surface. The vacancy islands typically form a nearly uniform array with a separation of about 5 nm which is close to the observed length scale of compositional fluctuations in InGaN alloys, thus providing a possible source of the bulk compositional fluctuations.

3:45 PM G2.7
A QUANTITATIVE ANALYSIS OF COMPOSITION FLUCTUATIONS IN InGaN QUANTUM WELLS. P. Ruterana, S. Kret, ESCTM-CRISMAT, Institut des Sciences de la Matiere et du Rayonnement, Caen, FRANCE; B. Damilano, N. Grandjean, J. Massies, Centre de Recherche sur l' Hetero-Epitaxie et ses Applications (CRHEA - CNRS), rue Bernard Gregory, Sophia-Antipolis, Valbonne, FRANCE.

The high intensity emission of InGaN based light emitting diodes has been attributed to the formation of quantum dots in the ternary layer. However a controversy still exist on their size and composition. In this work, we have carried out structural analysis of layers on a series of InGaN/GaN quantum wells grown by molecular beam epitaxy. Varying the well thicknesses from 1 to 5 nm with an indium composition of 15-20% allows to tune the emission wavelength and to cover the visible spectrum from blue to red at 300 K. For their characterisation, we have measured the local deformation of the lattice fringes and correlated it to the changes in composition. This procedure uses the Vegard law and locally connects the lattice parameters to the composition of the layer. By taking the necessary care, it is possible to estimate the local composition fluctuation inside these layers. This type of measurement is critical for very narrow QW. The validation of obtained deformation maps was checked by image simulations. One interesting result is the possibility to determine the composition changes inside wells of thickness close to 1 nm which allowed us to have better insights on the InGaN alloy properties.

4:00 PM G2.8
In SEGREGATION EFFECTES ON OPTICAL AND DOPING PROPERTIES OF InAlGaN FOR UV EMITTING DEVICES. Hideki Hirayama[1], Atsuhiro Kinoshita[1,2], Takuya Yamanaka[1,2], Akira Hirata[2], and Yoshinobu Aoyagi[1], [1]RIKEN (The Institute of Physical and Chemical Research), [2]Waseda Univ.

We for the first time demonstrate room temperature intense ultra-violet (UV) emission wavelength ranging 300-340nm and also high hole conductivity with Mg-doping for wide bandgap (~4eV) material by using In segregation effects in InAlGaN alloy. Up to now, blue and violet laser diodes (LDs) or light emitting diodes (LEDs) were realized by using InGaN quantum wells (QWs). However, UV emitting devices are not yet realized, because not only UV emission of (Al)GaN is too weak at room temperature, but also it is difficult to obtain hole conductivity for wide bandgap AlGaN. In this report, we propose to use In segregation effect for the purpose to obtain room temperature bright UV emission of 300nm-band and also high hole conductivity of wide bandgap AlGaN. Samples were grown at 76 Torr on 6H-SiC(0001) substrate by metal-organic vapor-phase-epitaxy (MOVPE). $In_xAl_yGa_{1-x-y}N$ quaternary was grown at 830°C on $Al_{0.1}Ga_{0.9}N$ buffer layer. Firstly, we investigated Al and In incorporated effects into undoped InGaN and AlGaN, respectively. We found that the InGaN (In:2%) emission was drastically enhanced by the increase of Al flow, which is caused by the increase of In incorporation induced by the Al incorporation. We also found that the AlGaN emission is drastically enhanced by the several percent incorporation of In. The photoluminescence (PL) intensity of $In_{0.05}Al_{0.34}Ga_{0.61}N$ was three orders of magnitude larger than that of AlGaN with the same bandgap and thickness. We confirmed the crystal quality of AlGaN is much improved by XRD measurement due to the In incorporation. Then, we fabricated multi- (M-) QW structures consisting of 1-5nm-thick $In_{0.05}Al_{0.34}Ga_{0.61}N$ wells and 6nm-thick $In_{0.02}Al_{0.60}Ga_{0.38}N$ barriers. We obtained intense PL emission of 300-340nm at room temperature. The emission of the InAlGaN MQWs was as strong as that obtained from InGaN QWs at room temperature. In segregation was clearly observed from cathode-luminescence (CL) from single- (S-) QW samples which is considered to improve emission efficiency. Then, we grew Mg-doped InAlGaN with the same growth condition. We obtained hole concentration of 3×10^{17} cm^{-3} by hole measurement for Mg-doped $In_{0.05}Al_{0.34}Ga_{0.61}N$ in spite of such a large Al content. In segregation was also observed by CL for bulk InAlGaN.

4:15 PM G2.9
ORGANIZED PHASE SEPARATION IN GaInAlN QUATERNARY ALLOYS. S.M. Bedair[1], N.A. El-Masry[2], S. LeBuoeff[1], and M. Behbehani[2]. [1]Electrical and Computer Engineering Department, North Carolina State University, Raleigh, NC; [2]Materials Science and Engineering Department, North Carolina State University, Raleigh, NC.

Phase separation has been previously observed in several ternary III-Nitride alloys. We report on the observation of separated phases during the growth of $Ga_{1-x-y}In_xAl_yN$ quaternary alloys. These $Ga_{1-x-y}In_xAl_yN$ quaternary alloys were grown in the temperature range of 800-870°C in an atmospheric pressure MOCVD system. The alloys' composition ranged from $0<x<0.1$ and $0<y<0.26$ for the In and Al, respectively. The films were characterized by x-ray diffraction, transmission electron microscopy and SIMS. Highly regular self-assembled separated phases in the form of alternating layers were observed in these quaternary alloys. The structure has alternating layers of high values of x and y with an adjacent layer of low values in x and y forming a unique self-assembled alternating layered structure. This phenomenon covered the entire thickness of the quaternary layers. This is in contrast with the separated phases observed in the ternary InGaN alloys. We will report a model to explain this ordered

phase separation and its impact on the optical and structural properties.

4:30 PM G2.10
COMPARATIVE ROLES OF AlN AND GaN NUCLEATION LAYERS IN THE GROWTH OF GaN BY METAL ORGANIC CHEMICAL VAPOR DEPOSITION. M. Gonsalves[1], Wook Kim[2], V. Narayanan[1], and S. Mahajan[1,2]. [1]Chemical and Materials Engineering Department and Center for Solid State Electronics Research, Arizona State University, Tempe AZ; [2]Materials Research Science and Engineering Center, Arizona State University, Tempe, AZ.

We have investigated the comparative roles of AlN and GaN nucleation layers (NLs) in the growth of GaN buffer layers by metal organic chemical vapor deposition using atomic force microscopy and transmission electron microscopy. Compared to the low temperature GaN NLs, AlN NLs provide higher density of nucleation sites for the growth of GaN overlayers. Differences and similarities in nucleation mechanism of high temperature GaN islands on AlN and GaN NLs will be discussed. Atomic force microscopy observation on the progression of coalescence of high temperature GaN islands deposited on AlN NLs show that planarization of the growth surface is achieved in a shorter time as compared to growth on GaN NLs. This observation can be rationalized in terms of the differential between the sizes and densities of high temperature GaN islands seen on the two types of NLs. Ramification of these results in the growth of high quality heterostructures will be discussed. The authors would like to gratefully acknowledge support for this work through DOD-MURI grant F49620-95-1-0447 and MRSEC grant 001081900.

4:45 PM G2.11
MORPHOLOGICAL EVOLUTION DURING GROWTH OF InGaN LASER DIODES ON LATERALLY OVERGROWN GaN ON SAPPHIRE. Monica Hansen, Paul Fini, James S. Speck, Steven P. DenBaars, University of California Santa Barbara, Departments of Materials and Electrical and Computer Engineerng, Santa Barbara, CA.

The morphological evolution of InGaN laser diodes on lateral epitaxial overgrown GaN on sapphire was investigated to understand the effect of dislocations on the surface morphology and subsequently on device performance. Though this effect is not fully understood, implementations of lateral epitaxial overgrowth (LEO) and AlGaN/GaN modulation-doped strained-layer superlattices in the laser structure have led to increased lifetimes. This reduction in dislocation density by mask blocking in the LEO technique leads to more efficient, lower threshold current density, longer lifetime lasers diodes. Atomic force microscopy (AFM) was used to investigate the surface morphology for lasers grown on LEO GaN and lasers grown on sapphire, which was significantly different for the two structures. The lasers on sapphire show uniformly distributed small spirals which are formed around a threading dislocation with a screw component. The laser structure grown on the LEO GaN exhibits large spirals in the dislocated window regions, but does not show spirals in the nearly-dislocation free wing region. To investigate the origin and evolution of the spiraled surface morphology, a growth-interrupt series was performed on fully coalesced LEO GaN on sapphire. The laser structure was grown step-wise with growth terminated after the InGaN compliance layer, the n-AlGaN/GaN SLS cladding layer, the InGaN/InGaN:Si (multiple-quantum well) MQW active region, and after the p-AlGaN/GaN SLS cladding. Significant spiraling occurs during the growth of the active region due the high driving force conditions present in MOCVD reactor environment for InGaN growth. The surface morphology for the n-cladding layer is fairly smooth, and the p-cladding smoothens the spiral initiated in the InGaN to a certain extent, but cannot recover surface morphology changes present prior to the active region. Cathodoluminescence (CL) and photoluminescence (PL) will be carried out to investigate the effect on spiral size and distribution on optical properties.

SESSION G3: POSTER SESSION
GROWTH AND CHARACTERIZATION
Monday Evening, November 27, 2000
8:00 PM
Exhibition Hall D (Hynes)

G3.1
CARBON-HYDROGEN COMPLEXES IN METALORGANIC CHEMICAL VAPOR DEPOSITION GROWN GaN. M.O. Manasreh, Department of Electrical & Computer Engr., University of New Mexico, Albuquerque, NM; C.A. Tran and I. Ferguson, EMCORE Corp., Somerset, NJ.

Localized vibrational modes (LVMs) of carbon-hydrogen complexes in metalorganic chemical vapor deposition grown GaN on sapphire were studied using a Fourier-transform infrared spectroscopy technique. The absorbance spectrum exhibits a structure in the spectral region of 2840 - 2965 cm-1 with three peaks related to the stretching modes of C-H defect complexes. The C-H LVMs were observed in undoped, Si- and Mg-doped samples as well as in samples contaminated with O2. It is observed that the intensity and the frequencies of the LVMs are sample dependent perhaps due to the variation of the strains generated by the presence of high dislocation densities. On the other hand, these LVMs were observed to be independent of the dopant densities. One of the intriguing observations of this study is that the C-H LVMs were not observed in high quality samples as judged by the photoluminescence spectra suggesting that the incorporation of carbon and hydrogen and the formation of C-H complex defects depend strongly on the growth conditions. Detail discussions and correlation between the LVMs and photoluminescence spectra will be presented.

G3.2
A NEW MECHANISM IN THE GROWTH PROCESS OF GaN BY HVPE. Agnës Trassoudaine, Eric Aujol, Robert Cadoret, LASMEA, Aubiëre, FRANCE; Tania Paskova, Bo Monemar, Dept of Physics and Measurements Technology, Linköping, SWEDEN.

We present the results of GaN growth by HVPE under a variety of experimental conditions. The results are analyzed with a model based on two desorption mechanisms of chlorine. First, the experimental results obtained with nitrogen as carrier gas with two different reactors are discussed. For nitrogen as the carrier gas, the growth is kinetically controlled by the desorption of the $GaCl_3$ gaseous species. We discuss the role of the composition of the vapor phase over the substrate by analyzing the parasitic nucleation upstream and above the substrate as well as the growth rate. In each case, the computed supersaturation in the mixing and in the deposit zone is lower than the experimental one. The comparison between the experimental results and the calculations leads to the conclusion of the non-equilibrium of the $GaCl_3$ in the vapor phase. Experiments in a mixed nitrogen and hydrogen gas ambient were also performed. The parasitic deposit on the quartz before the substrate was then controlled by adding HCl and/or hydrogen in the main flow. Positive supersaturation leading to positive growth rates over the substrate was obtained without parasitic nucleation upstream. Conditions yielding zero supersaturation over the substrate were obtained and are discussed. The morphology, the growth rate and the optical properties of the GaN epilayer depend on the percentage of hydrogen in the nitrogen carrier gas. The calculations show that the actual composition of the vapor phase over the substrate is one of the most relevant input parameters of the model. To obtain a good agreement between the experiments and the calculations a new growth mechanism involving desorption of $GaCl_2$ had to be taken into account.

G3.3
INCORPORATION OF MAGNESIUM AND BERYLLIUM DURING RF-PLASMA GROWTH OF GaN BY MOLECULAR BEAM EPITAXY. T.H. Myers, A.J. Ptak, Lijun Wang and N.C. Giles, West Virginia Univ, Dept of Physics, Morgantown, WV; M. Moldovan, C.R. Da Cunha and L.A. Hornak, West Virginia Univ, Dept of Electrical Engineering, Morgantown, WV; C. Tian, R.A. Hockett, S. Mitha and P. Van Lierde, Charles Evans and Associates, Redwood City, CA.

Step-doped structures of both magnesium and beryllium have been grown in GaN and analyzed using secondary ion mass spectrometry. Dopant incorporation was studied as a function of substrate temperature and dopant flux for Ga-polarity and N-polarity GaN. Incorporation is different for each polarity, with Mg incorporating by up to a factor of 20 times more on the Ga-face, while Be incorporates more readily on the N-face. The effect of atomic hydrogen on the incorporation kinetics of both Mg and Be is also discussed. Both Mg and Be show classic signs of surface segregation during growth. Etching experiments have been performed in order to remove the Be-rich top layer from uniformly doped GaN:Be. Differences in the photoluminescence (PL) measurements performed before and after the etch have been observed. PL and Hall effect measurements also indicate that Be is a p-type dopant with an optical activation energy less than 100 meV, but as-grown samples appear to be heavily compensated. This work was supported at WVU by ONR Grant N00014-96-1-1008 and was monitored by Colin E.C. Wood.

G3.4
PHASE SEPARATION IN Zn-DOPED InGaN GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION. Z.C. Feng, S.J. Chua, Institute of Materials Research & Engineering, SINGAPORE; R. Liu, A.T.S. Wee, National Univ of Singapore, Dept Physics; K.P.J. Williams, G.D. Pitt, Renishaw plc, UNITED KINGDOM.

The ternary alloy InGaN covers the direct-band-gap energy ranging

from 1.9 eV (InN) to 3.4 eV (GaN) and is a key material in the GaN-based blue/UV light emitters/lasers and high-power electronic devices. A large lattice mismatch between GaN and InN (10%) causes a solid phase miscibility, and when growing InGaN with x(In) larger than 6%, a phase separation and composition inhomogeneity can easily occur. Also, the InGaN phase separation in InGaN-GaN quantum well structures may produce quantum dot - like features to induce the exciton localization to enhance photoluminescence (PL) emissions. The study on the phase separation in InGaN materials is an important issue and also the focusing of this study. A series of Zn-doped InGaN thin films were epitaxied on the top of 1-2 micron thick GaN grown on sapphire by metal organic chemical vapor deposition. They were studied by a combination of high resolution X-ray diffraction (HR-XRD), micro-PL and secondary ion mass spectroscopy (SIMS). HRXRD exhibits a GaN band and a single band from InGaN for samples without phase separation, but two or more InGaN bands corresponding to different x(In) for samples with phase separation. PL emissions from InGaN spread over a wider energy ranges and were modulated by the interference effects. However, excitation power dependence measurements clearly reveal 2-sets of PL emissions for samples with phase separation, but only 1-set for samples without phase separation. SIMS data showed that phase separated InGaN:Zn films possess a high Zn concentration near the InGaN-GaN interface and non-uniform distribution of In content, while InGaN:Zn films with no In-phase separation have low Zn concentration and more flat In and Zn distribution over the entire InGaN layer. These interesting results are correlated to the growth process and microstructural properties.

G3.5
INITIAL STAGE GaN GROWTH ON VICINAL SiC(0001) SUBSTRATE BY MOLECULAR BEAM EPITAXY. S.H. Cheung, M.H. Xie, L.X. Zheng, S.Y. Tong, University of Hong Kong, HONG KONG.

We have followed morphological evolution of wurtzite GaN films during initial stage nucleation and growth on vicinal SiC(0001) substrate. Film growth is realized by molecular beam epitaxy (MBE), while surface morphology is examined by ultrahigh vacuum scanning tunneling microscopy (STM). A substrate temperature of 650°C has been used in this investigation. To reflect the surface of a growing film, the sample is thermally quenched for different growth stages. In situ reflection high-energy electron diffraction patterns suggest little change of the surface upon thermal quenching. As is well known, initial stage nucleation plays a crucial role in determining the subsequent growth morphology and film's structural quality. We observed the dominance of spiral mounds on films grown on nominally flat SiC(0001) substrates, while such a spiral feature is absent from films grown on vicinal substrates. This distinction is shown to reflect the differences in their initial stage nucleation of the two films. On a vicinal substrate, initial GaN growth proceeds by 3D islands formation at step edges, similar to that on a flat surface although the latter occurs at random sites. As the islands become larger, they are seen to extend preferentially along the steps of the vicinal substrate, therefore, the islands are elongated. This is contrasted to that on a flat substrate where neither site preference nor island elongations are observed. Once the islands are coalesced, the vicinal film can be characterized by a step-bunched surface. Finally, as the deposition continues, the bunched steps dissolves into equally spaced, double bilayer height steps. For a flat film, coalescence leads to formation of spiral mounds, each associates with a threading screw dislocation. We have analyzed the sidewalls of the islands as well as the slopes of the step-bunches. Their evolution with time will be summarized in this presentation.

G3.6
GALLIUM NITRIDE FILMS FROM LIQUID PRECURSORS. Manfred Puchinger, Thomas Wagner, Max-Planck-Institut fuer Metallforschung, Stuttgart, GERMANY; David J. Kisailus, Frederick F. Lange, Materials Department, University of California, Santa Barbara, CA.

In general, GaN films are grown by MOCVD or MBE techniques. Optimization of the processing has lead to electronic-device quality materials. GaN films can also be grown from liquid precursors. In this technique, precursor solutions are applied to a substrate surface by spincoating. During a heat treatment in ammonia, the polymeric film transformed into crystalline GaN. In this presentation two different precursor systems will be introduced, both leading to crystalline GaN films on sapphire substrates. Thin precursor films turned into facetted, epitaxial GaN layers (up to ca. 20 nm) on sapphire-C and -R plane substrates. Such films may be used as buffer layers. However, heat treatment of thicker films resulted in polycrystalline GaN materials. The microstructure of the films was investigated by SEM and TEM.

G3.7
Mn-DOPING OF GaN GROWN BY METAL ORGANIC VAPOR PHASE EPITAXY. Roman Y. Korotkov, Joel M. Gregie and Bruce W. Wessels, Northwestern Univ, Dept of Materials Sceince and Engineering, Evanston, IL.

GaN epitaxial thin films doped with Mn were grown by metalorganic vapor phase epitaxy (MOVPE). Mn-doped epilayers were semi-insulating both before and after a high temperature annealing treatment. Using photoluminescence spectroscopy, a new broad band was observed at 1.3 ± 0.02 eV in the infrared spectra with a full width half maximum of 0.3 ± 0.02 eV. This band is tentatively attributed to a transition from the conduction band to a Mn deep acceptor level. From infrared absorption spectroscopy measurements, the energy of the deep acceptor level was found to be 1.4 ± 0.1 eV. The measured energy level is in good agreement with first principle calculations.

G3.8
OPTIMIZATION OF THE GaN EPILAYER QUALITY USING IN-SITU REFLECTANCE MEASUREMENTS. S. Ruffenach-Clur, M. Moret, O. Briot, N. Moreaud, J. Calas, R.L. Aulombard, GES, Université Montpellier II, Montpellier, FRANCE.

Although a tremendous amount of work has been done these last years on the nitride semiconductor system, a lot is still to be understood regarding the growth mechanisms of GaN. The standard GaN MOCVD growth process includes the low temperature deposition of a buffer layer, followed by an anneal at high temperature, and the GaN layer is then deposited on such a re-crystallized buffer. The number of process parameters which can be used to tune the growth is very large (temperatures, times, thicknesses, molar flow rates and ratios ...) and, due to the coupling between them, the role of each one is not clearly understood. In this paper, we present systematic series of growth experiments, where in-situ reflectance monitoring was used and correlated to ex-situ optical characterization of the samples by photoluminescence and reflectivity at low temperature (2K), and sample morphology characterization by microscopy. Here, we demonstrate that the buffer (nucleation) layer has a determining effect on the overall layer quality. The buffer layer growth temperature was not found to be a very sensitive parameter, while the amount of re-crystallization is. The re-crystallization time is not really a parameter, since increasing it above a given threshold does not affect further the recrystallization. Surprisingly, the amount of ammonia present in the gas phase has a determining effect on the recrystallization behavior of the buffer. Another interesting point is the sensitivity versus growth temperature for the main GaN layer, which was found to affect the initial stages of the growth in a drastic manner when changed by only 10°C. In-situ reflectance allowed us to tune precisely our process and to obtain GaN layers with 500 cm^2/Vs electron mobility at room temperature and photoluminescence fwhm of 1.7 meV at 2K for the donor-bound exciton.

G3.9
MICROSTRUCTURE OF GaN GROWN ON (11-20) SAPPHIRE. P. Ruterana, F. Degave, G. Nouet, ESCTM-CRISMAT, Institut des Sciences de la Matiëre et du Rayonnement, Caen, FRANCE; A. Wickenden, M. Twigg, D. Koliske, Electronics Science and Technology Division, Naval Research Laboratory, Washington, DC.

Most of the work done on GaN has taken into account layers grown on the (0001) sapphire. However one would expect the growth on (11-20) to lead to different structural defects. As has been shown, in one direction, the mismatch is rather small. In this work, we have carried out structural analysis of layers and interfacial relationship. Inside the layers, the density of defects is comparable to that found conventionally in layers grown on top of (0001) sapphire. The growth mode is also mosaic with grain size over 10-20 microns. One interesting result is the interface structure, it is rather different to conventional growth in which one expects a flat or stepped interface with large distance between steps. In this case, the interface is found to be rough at the atomic scale; this roughness has a random distribution.

G3.10
CHEMICAL ORDERING IN AlGaN LAYERS GROWN BY MOCVD. P. Ruterana, G. De Saint-Jores, ESCTM-CRISMAT, Institut des Sciences de la Matiere et du Rayonnement, Caen, FRANCE; S.M. Laugt, F. Omnes, Centre de Recherche sur l' Heteroepitaxie et ses Applications, Sophia-Antipolis, Valbonne, FRANCE; E. Bellet-Amalric, DRFMC/SP2M/SGX CEA/Grenoble, FRANCE.

One of the most interesting application of wurtzite gallium based nitride compounds will be to provide optoelectronic devices from 6.2eV (AlN) to 1.89eV (InN). This will depend on the possibility to grow wurtzite AlGaN and InGaN ternary alloys. As expected, the most difficult region is InGaN due to the large misfit between GaN and InN (= 10%), in this case, ordering, phase separation and growth instabilities have been reported. The misfit between AlN and GaN is smaller (2.5%) and one would expect more stable growth of AlGaN.

However, it is in this system that ordering along the c axis between AlN and GaN was reported for the first time. In this work, we have found that the growth of AlGaN may be more complicated. Not only the wurtzite lattice can be decreased to simple hexagonal by AlN/GaN ordering along the c axis, but the growth can lead to other types of stackings. Even in the low Al composition range, 10 - 15%, we have found that three processes can operate: 1. Ordering into AlN/GaN as two simple hexagonal sublattices. 2. The 3:1 ordering which has been recently reported to occur in InGaN. 3. A new type of ordering where diffraction experiments (XR and electron diffraction) detect superlattice reflection with a period close to 3 nm. The most adequate model which was found to take this into account shows that, in these growth conditions, the system has preferred to form one AlN cell in between 5 GaN cells, leading to a 10:2 ordering.

G3.11
GROWTH OF As-DOPED GaN AND N-DOPED GaAs BY MBE. Carl S. Davis, Sergei V. Novikov, Tin S. Cheng, Richard P. Campion, C. Thomas Foxon, University of Nottingham, School of Physics and Astronomy, Nottingham, UNITED KINGDOM; Andrew J. Winser, Ian Harrison, University of Nottingham, School of Electrical and Electronic Engineering, Nottingham, UNITED KINGDOM.

We demonstrate for the first time strong blue emission ~2.6eV for GaNAs grown by molecular beam epitaxy (MBE). We have studied the growth of N-rich GaNAs on sapphire substrates using a growth temperature of ~800°C. Reflection high-energy electron diffraction (RHEED), photoluminescence (PL), X-ray diffraction (XRD), atomic force microscopy (AFM) and Auger electron spectroscopy (AES) have been used to examine the structural and optical properties of our material. Our findings indicate that As affects significantly the surface reconstruction of GaN. For unintentionally doped GaN samples, a (4 × 4) reconstruction associated with excess surface Ga appears during cooling. However, with As-doped samples, a (2 × 2) and mixed domain pattern is observed by RHEED upon cooling. AFM has been used to demonstrate the effect of As as a surfactant in the epitaxial growth of GaN. With low As fluxes, our samples exhibit macroscopically flat islands with clearly visible atomic steps and the surface roughness is seen to improve with increasing As overpressure. AES reveals that the surface concentration of As in GaNAs samples is independent of the As flux during growth for the wide range of 10^{-9} to 10^{-5} Torr of As. Furthermore, the surface As concentration is virtually unaffected by the choice of As_2 or As_4 as the growth species. Besides revealing strong blue emission, our PL results lead us to propose a growth mechanism for As-doped GaN in which cubic GaN is formed from GaAs by a direct substitution of N and As atoms. The strong blue emission suggests that GaNAs may be a suitable replacement for InGaN in opto-electronic devices grown by MBE. We are presently extending our studies to examine the growth of N-doped GaAs (As-rich GaAsN) on misoriented GaAs substrates to study the possible influence of vicinal growth surfaces upon nitrogen solubility in the alloy.

G3.12
GROWTH OF HEXAGONAL GaN ON Si(111) COATED WITH A THIN FLAT SiC BUFFER LAYER. Deliang Wang, Y. Hiroyama[a], M. Tamura, M. Ichikawa, Joint Research Center for Atom Technology, Angstrom Technology Partnership (JRCAT-ATP), Tsukuba, JAPAN; S. Yoshida, The Furukawa Electric Co., Ltd., Yokohama, JAPAN. [a]Present address: Sumitomo Chemical Co. Ltd., Tsukuba, JAPAN.

The relatively low lattice mismatch between SiC and GaN (~3%) makes SiC a useful substrate for GaN growth. The SiC(111) surface, which is identical to the (0001) plane of 6H-SiC, is a good match for subsequent growth of hexagonal III-N films. In this paper we report our recent work on the growth of hexagonal GaN grown on Si(111) coated with a 2.5- nm-thick SiC buffer layer to develop a technology for GaN growth on Si substrate. The thin flat SiC buffer layer was grown through carbonization of the Si(111) surface in C_2H_2. The surface roughness of SiC on Si(111) was 0.5 nm. A flat SiC surface is needed to reduce the structure defects in GaN film because stacking faults and dislocations can originate from rough regions of the SiC surface. GaN films were grown under both N- and Ga-rich conditions. Our results showed that the growth mode and microstructure of GaN depended strongly on the Ga/N flux ratios. Under N-rich growth condition, the growth mode was three-dimensional, GaN showed statistical roughening of the surface and a characteristic columnar structure with a rough surface. Under Ga-rich condition, the GaN growth was two-dimensional. GaN films with a flat surface and an almost stacking-fault- free microstructure were obtained. The two-dimensional growth mode was facilitated by strong wetting between Ga and SiC(0001) at the first Ga-layer deposition on SiC. The PL spectra measured at 77 K and at room temperature showed both the near-band-edge and the yellow-band (YL) peaks. Our plan and cross-sectional TEM observations and recent studies suggest that the YL may be related to pure and/or mixed screw dislocations in the GaN films. This work was supported by NEDO.

G3.13
SURFACE MORPHOLOGY AND COMPOSITION CHARACTERIZATION IN THE INITIAL STAGES OF AlN CRYSTAL GROWTH. B. Liu, Y. Shi, L. Liu and J.H. Edgar, Department of Chemical Engineering, Kansas State University, Manhattan, KS; D.N. Braski, Oak Ridge National Laboratory, Oak Ridge, TN.

The morphology and composition of AlN on 6H-SiC(0001) at the initial stage of crystal growth by sublimation re-condensation was investigated by SEM and Auger. Discontinuous AlN coverage occurred after 15 minutes under a series of different temperatures and pressures to observe the effect of pressure and temperature on the growth rate and crystal morphology. The AlN nuclei size and distribution density increase from 1800°C to 1900°C at 500 torr of pure N_2. At 1850°C, by decreasing the system pressure from 700 torr to 200 torr, the sizes and distribution densities increased, and the AlN began to merge together to form flat top AlN crystals. High magnification SEM shows that the SiC decomposes leaving hexagonal hillocks. Simultaneously, the AlN preferentially nucleates on these SiC hillocks, rotated 15° to 30° with respect to the SiC substrate. The chemical composition of the substrate, and different AlN crystal facets were characterized by scanning Auger microscopy. Bare substrate area was stoichiometric SiC, indicating insignificant loss of Si and little conversion to silicon nitride. The top of small hillocks formed on the SiC substrate were Si and C rich with only small amounts of Al and N. The AlN(0001) crystal plane was primarily Al and N. In contrast, Si and C were detected on the inclined crystal facets, along with Al and N, indicating Si and C incorporates in the AlN at the initial stages of growth on specific crystal planes.

G3.14
HIGH SELECTIVE PHOTOENHANCED WET ETCHING OF GaN FOR DEVICE FABRICATION AND DEFECTS INVESTIGATION. P. Visconti, Virginia Commonwealth University, Richmond, VA and Istituto per lo Studio di Nuovi Materiali per l' Elettronica, CNR, Lecce, ITALY; M.A. Reshchikov, K.M. Jones, M.H. Zhang, J. Cui, F. Yun, D.F. Wang, R. Cingolani, and H. Morkoc, Virginia Commonwealth University, Richmond, VA; C.W. Litton, AFRL, Wright Patterson AFB, OH; R. Molnar, MIT Lincoln Laboratories, Lexington, MA.

Photoenhanced electrical chemical (PEC) wet etching has been shown to be suitable for GaN-based device fabrication as well as for dislocation-density estimation in n-GaN films. We report on PEC etching of n-GaN samples grown by MBE and HVPE methods in unstirred aqueous KOH solution under He-Cd laser illumination. Characterization of the etched samples was carried out using scanning electron microscopy (SEM), atomic force microscopy (AFM) and cross-sectional AFM. At low illumination densities (10-100 mW/cm^2), the plane-view SEM and AFM analyses reveal sub-100 nm scale threading vertical wires on the etched surfaces. The calculated density ($5x10^8$-$2x10^9$) is in agreement with dislocation density found by transmission electron microscopy (TEM). Using cross-sectional AFM, we find that these vertical wires are ~1μm high and are perpendicular to the sapphire surface. At high illumination densities (10 W/cm^2), we obtain a high etch rate (0.1 μm/min) that leaves a smooth surface with no free-standing wires. With both etching conditions, we report on high selective etching in AlN/GaN sample (AlN is an etch stop); the selectivity is due to the etching mechanism of the PEC process. In some cases, samples that cannot be etched under normal conditions, where the band bending is too small to confine the holes to the surface for them to partake in the etching process, can be etched with the application of a voltage to the sample during the etching process. In this case, the etch rate of the GaN depends on the both the polarity and the magnitude of the voltage applied.

G3.15
SIMULATION OF STRESS GENERATION DURING GaN LATERAL EPITAXIAL OVERGROWTH. Zhaohua Feng, Edward G. Lovell, Roxann L. Engelstad, Computational Mechanics Center; Thomas F. Kuech, Dept. of Chemical Engineering; University of Wisconsin, Madison, WI.

Lateral epitaxial overgrowth continues to be a promising technique for producing GaN films. In the process of film growth, stresses are generated by lattice mismatch between the GaN and its sapphire substrate, as well as by thermal expansion mismatch. The stresses may lead to dislocations, which adversely affect the film quality. It is very difficult to directly measure the stresses in real time during GaN film growth. Computational simulation of stress evolution is more feasible and is presented here. The entire film growth procedure has been subdivided into sequential stages, i.e., the GaN seed layer growth on the sapphire substrate, silicon dioxide deposition on the seed layer, etching to create a stencil mask, GaN re-growth on the seed layer through the stencil windows, lateral and vertical growth

over the silicon dioxide, gap closure, GaN continuous vertical growth and then cool-down to room temperature. A series of numerical models have been created to simulate the stress generation and development at different stages. Lattice mismatch strain and temperature variation are considered as input parameters. Submodeling techniques are used to simplify the computations and improve solution accuracy. The constraint at the interface between the silicon dioxide and the GaN is assumed as a slip condition. Transient finite element techniques are applied to analyze each model for all stress, strain and displacement components. The output results from the last stage are used as initial conditions for the current stage; results of the current stage are input as initial conditions for the next stage. By combining the results of all stages, the stresses at any time during the entire film growth process are determined. The simulation models can be used for demonstrating and explaining the dislocation generation mechanism in GaN lateral epitaxial overgrowth, predicting stresses and optimizing process parameters.

G3.16

EFFECT OF N_2 PLASMA TREATMENTS ON DRY ETCH DAMAGE IN N- AND P-TYPE GaN. D.G. Kent, K.P. Lee, M.E. Overberg, C.R. Abernathy, S.J. Pearton, Department of Materials Science and Engineering, University of Florida, Gainesville, FL; A.P. Zhang and F. Ren, Department of Chemical Engineering, University of Florida, Gainesville, FL.

Exposure of GaN to N_2 plasmas at $<400^{\circ}$C is reported to improve Mg acceptor reactivation efficiency in p-GaN and to partially restore the electrical properties of plasma damage in n-GaN (ref. Kim et. al., Appl. Phys. Lett. 76, 3079 (2000); Lee et. al., J. Appl. Phys. 87, 7667 (2000)). We have created 500$\AA$ thick damaged regions in n- and p-GaN using ICP Ar plasmas, and subsequently examined the effect of N_2 plasma exposures at temperatures from 250-600°C on the damage recovery using diode reverse breakdown voltage and barrier height measurements. These measurements allow a rough determination of the nitrogen incorporation depth as a function of temperature as well as the concentration incorporated. The effectiveness of the nitrogenation treatment for damage recovery is compared to thermal annealing and wet removal processes.

G3.17

INVESTIGATION OF BUFFER LAYERS FOR GaN GROWN BY MBE. M.H. Zhang, J. Cui, F. Yun, M.A. Reshchikov, K.M. Jones, D.F. Wang, and H. Morkoc, Virginia Commonwealth University, Richmond, VA; P. Visconti, Virginia Commonwealth University, Richmond, VA and Istituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY; C.W. Litton, AFRL, Wright-Patterson AFB, OH.

The structural quality of the buffer layer juxtaposed to the substrate is pivotal in attaining high quality GaN layers. In MBE deposition, low temperature, medium temperature and high temperature AlN buffer layers are at the disposal of the grower. There are quite a few reports, some discussing the benefits of high temperature buffer layers and others doing the same for low temperature buffer layers. The reports emanate from different laboratories and due to stringent parameter control required, it is difficult to compare one type of buffer with another. To circumvent this, we have undertaken an investigation wherein these varieties of buffer layers were grown on nitridated sapphire substrate under similar conditions for a comparative analysis. In addition to the single buffer layers of both GaN and AlN varieties, some combinations of stacked buffer layers including cases where these buffer layers were separated by GaN layers were employed. Structural analysis by high resolution X-Ray diffractometry, topological analysis by AFM were carried out to assess the quality of these buffer layers. In order to carry out electrical and optical investigations, GaN and AlGaN/GaN modulation doped structures were grown on these buffer layers and analyzed. In one series of layers, defect revealing Photo Enhanced Chemical etching was employed for a quantitative determination of structural defect density. Moreover, unique defect blocking structures were employed in conjunction with optimized buffer layers to obtain excellent optical and structural properties in very thin films of GaN on sapphire substrates. The details of the growth process, which employed both RF nitrogen and ammonia sources for nitrogen, and properties of films will be discussed.

G3.18

SURFACE SEGREGATION AND PHASE SEPARATION AS THE FACTORS AFFECTING In INCORPORATION DURING MOVPE AND MBE OF InGaN. Roman A. Talalaev, Eugene V. Yakovlev, Sergey Yu. Karpov, Soft-Impact Ltd., St. Petersburg, RUSSIA; Yuri N. Makarov, Fluid Mechanics Dept, Univ of Erlangen-Nuernberg, Erlangen, GERMANY.

Low In incorporation efficiency in MOVPE and MBE of InGaN is still a key problem for blue/green LEDs and laser technology. It is found to be sensitive to many factors: temperture/pressure growth conditions, gaseous atmosphere (amount of hydrogen), substrate (strain effects), etc. Experimentally, extremely high lateral non-uniformity is observed in the grown InGaN epilayers being attributed to phase separation. In this paper we consider two phenomena affecting In incorporation – surface segregation and phase separation occuring during the epitaxial growth. In surface segregation is analyzed with a novel rate-equation approach verified by vast experimental data avialable for MBE of InGaAs. Growth temperature and elastic strain in the InGaN epilayer are found to be principal factors controlling In segregation. In the layers grown on sapphire or on SiC substrates the strain is partly relaxed due to a large density of dislocations. Only growth of InGaN on GaN can provide nearly uniform strain in the epilayers. For InGaN the model predicts the segregation length lower that that obtained for InGaAs. This is related to the fact that growth of InGaN occurs at higher temperatures. However, the calculated In coverage of InGaN surface is frequently comparable or higher that 1 monolayer. Hence, surface In, similarly to surface Ga, is expected to block almost totally the adsorption sites for ammonia. This should result not only to In incorporation supression but also to stop of growth under certain conditions. Assuming surface diffusion to be fast compared to the rate of species supply onto the growth surface, we consider effect of phase separation on InGaN growth. In this case two InGaN compounds of different compositions are simultaneously deposited on the wafer. The surface fraction corresponding to every compounds and their compositions are computed for typical conditions. The mean size of the InN-rich areas is estimated from the known density of the InN islands. The theoretical predictions are compared with the available experimental data on InGaN growth by MOVPE and MBE.

G3.19

EFFECTS OF OXYGEN ADDITION IN INDUCTIVELY COUPLED Cl_2/Ar PLASMA ON THE ETCH CHARACTERISTICS OF III-NITRIDES. Ji-Myon Lee, Ki-Myung Chang, Seong-Ju Park, Kwangju Institute of Science and Technology, Dept of Materials Science and Engineering and Center for Optoelectronic Materials Research, Kwangju, KOREA.

The etch characteristics of GaN, $Al_xGa_{1-x}N$, and $In_xGa_{1-x}N$ for device application have been examined in an inductively coupled plasma reactor using $Cl_2/Ar/O_2$ as an etchant gas. Etch rates and selectivities were strongly influenced by the flow rate of oxygen as well as the plasma parameters. Etch rates as high as 5500 $\AA$/min were obtained for GaN, 1850 $\AA$/min for $Al_{0.05}Ga_{0.95}N$, and 420 $\AA$/min for $Al_{0.1}Ga_{0.9}N$, and 2589 $\AA$/min for $In_{0.12}Ga_{0.88}N$. Moreover, the etch selectivities of GaN and the $In_{0.12}Ga_{0.88}$ over the $Al_{0.1}Ga_{0.9}N$ were as high as 24 and 32, respectively. These are the highest values ever reported for an AlGaN film with a relatively low Al composition (x=0.1). An x-ray photoelectron spectroscopy analysis of the etched surface showed that an Al-O bond was formed on the AlGaN surface during the $Cl_2/Ar/O_2$ plasma etching and the high selectivity thus obtained could be attributed to the etch-resistant aluminum oxide layer. This oxide layer could be easily etched off by an HF-based wet solution during the mask removal process. The surface morphology of an etched AlGaN, observed by an atomic force microscopy, was also influenced by the flow rate of oxygen. Furthermore, the leakage currents in Schottky diode on AlGaN surface which was selectively etched by $Cl_2/Ar/O_2$ plasma, were decreased compared to those etched by Cl_2/Ar plasma, probably due to the suppression of preferential loss of nitrogen.

G3.20

SURFACE MODIFICATION OF CUBIC GaN BUFFER LAYER GROWN BY METALORGANIC VAPOR PHASE EPITAXY. Akira Nagayama, Saitama Laboratory, Japan Radio Co., Ltd., Saitama, JAPAN; Ryuji Katayama, Jun Wu, Kentaro Onabe, Hidetaka Sawada, Eliko Takuma, Hideki Ichinose, Dept of Materials Science, University of Tokyo, Tokyo, JAPAN; Yasuhiro Shiraki, RCAST, University of Tokyo, Tokyo, JAPAN.

Anisotropic transport properties and the new feature of the hexagonal phase generation in cubic GaN films were previously reported. Carrier mobilities along [1-10] direction of cubic GaN films grown on on-axis GaAs (001) surface were approximately one tenth of those along [110] direction. In GaN films grown on the surface tilted by 4° toward the [1-10] direction, stacking faults were preferentially generated from GaAs surface, and on the (1-11) faces when the low-temperature grown GaN (LT-GaN) buffer layer is annealed in hydrogen ambient. However, the stacking faults were generated on the (-111) faces when annealed in arsenic ambient. In the present paper, in order to investigate these anisotropic properties, the features of the buffer layer as modified by thermal annealing are studied on the basis of atomic force microscope (AFM) and transmission electron microscopy (TEM) observations. An initial GaAs buffer layer of about 100nm in thickness was grown at 700°C by low-pressure (160 Torr) MOVPE. Then, a 20nm-thick GaN buffer layer (LT-GaN) was grown at 580°C. During the heating of the substrate up to 940°C for the high-temperature GaN growth, the LT-GaN buffer layer was exposed to either

hydrogen, or hydrogen plus arsine ambient. AFM observation shows the anisotropic surface modification on the surface tilted toward [1-10] (As step edge), but not toward [110] (Ga step edge). In the case of hydrogen plus arsine gas annealing for LT-GaN buffer layer, the step edge density of the LT-GaN buffer layer tilted towards [1-10] is less than the density on the surface tilted towards [110]. TEM observation reveals that stacking faults-free relaxation can be occurred if the step edges of GaAs surface have a five monolayers height. It is suggested that the anisotropic transport properties are caused by the orientation dependence of lattice relaxation at step edges.

G3.21
PHASE EQUILIBRIA IN THE METAL-Al-Ga-N SYSTEMS AND THE THERMAL STABILITY OF SCHOTTKY CONTACTS TO N-AlGaN. K.O. Schweitz and S.E. Mohney, Dept. of Materials Science & Engineering, The Pennsylvania State University, University Park, PA.

Electrical contacts to AlGaN are necessary for a variety of devices, such as heterojunction field effect transistors and certain UV detectors. For ohmic contacts, controlled metallurgical reactions are often necessary to achieve low resistance contacts. For Schottky barriers, contacts that have high barrier heights, low leakage currents, and adequate thermal stability to withstand high temperature processing and operation are desired. To achieve both of these goals, an understanding of the relevant phase equilibria in these systems and the thermodynamic driving forces for interdiffusion is valuable. We have previously estimated the phase equilibria in the *X*-Ga-N systems[1], where *X* denotes a transition metal. As a further step in understanding the Metal-Al-Ga-N systems, we now present a survey of the phase equilibria in the *X*-Al-N systems. There are fortunately more experimentally available phase diagrams for these systems than for the *X*-Ga-N systems; however, many of the diagrams are not available for the conditions of most interest for processing contacts and devices. Therefore, we have also used thermodynamic calculations to estimate the phase diagrams at 600 and 1000°C, and we have predicted the phases that will be stable on AlN when processed under different partial pressures of N_2 gas. Important phases in thermodynamic equilibrium with AlN under conditions of interest are found to be mainly transition metal nitrides, pure transition metals, and transition metal aluminides for the early, middle, and late transition metals, respectively. The stability of the late transition metal aluminides and the middle transition metals on AlN are found to be sensitive to changes in temperature and the pressure of the N_2 gas during processing. On the other hand, the stability of the early transition metal nitrides on AlN is relatively insensitive to temperature and N_2 pressure. We follow these predictions with experimental studies of the thermal stability of Schottky barrier contacts to n-AlGaN.
[1]S.E. Mohney and X. Lin, J. Electron. Mater. **25**, 811 (1996).

G3.22
CRACK FREE MOVPE GROWTH OF GaN/AlN AND GaN/InGaN MQW ELECTROLUMINESCENCE TEST STRUCTURES (ELT) ON (111) SILICON SUBSTRATES. A. Dadgar, J. Bläsing, S. Richter, A. Diez, J. Christen and A. Krost, Otto-von-Guericke Universität Magdeburg, Fakultät für Naturwissenschaften, Magdeburg, GERMANY; A. Alam, B. Schineller, M. Heuken, and H. Juergensen, AIXTRON AG, Aachen, GERMANY.

The advantages of the silicon (Si) substrate for the growth of AlGaN/GaN in comparison to sapphire or silicon carbide (SiC) are for instance very low cost for the mass production and much easier processing of LEDs. The main disadvantage of Si for the growth of GaN/AlGaN is, however, the formation of cracks for layer thicknesses of approximately 1 μm and above. With respect to this problem the growth of GaN/AlGaN and InGaN on silicon substrates (111) has been investigated in this work. The samples presented here have been grown in an AIX 200 RF MOCVD system, using TMGa, TEGa, TMAl, TMIn, NH3, SiH4 and CP2Mg as precursors. Reactor total pressures of 200 and 50 mbar and growth rates of 2.5 μm/h and 0.7 μm/h were used for the GaN:Si buffer and the AlN layer, respectively. We overcame the problem of cracks by the growth of two 15 nm thick low temperature silicon doped AlN (AlN:Si) intermediate layers following an approximately 32 nm thick low temperature AlN nucleation layer. Samples which employed AlN intermediate layers did not exhibit cracks whereas samples without, grown under the same conditions showed approximately 240 cracks/mm^2. The white light interferometry measurements show a thickness of about 1.3 μm with a standard deviation (std dev) of about 4% for all samples. GaN/GaInN ELT on Si (111) which show bright blue luminescence were also grown. Electrical, optical and structural properties will be presented and correlated to the growth conditions.

G3.23
Bi-DOPED GaN EPILAYERS AND LATERAL EPITAXIAL OVERGROWTH BY METAL ORGANIC VAPOR PHASE EPITAXY. L. Zhang, S.L. Gu, T.F. Kuech, Department of Chemical Engineering, S.E. Babcock, Department of Materials Science and Engineering, University of Wisconsin-Madison Madison, WI.

Bismuth and other elements have been suggested as possible surfactants in the GaN system. A previous report has indicated some changes in the GaN:Bi layer morphology, relative to undoped GaN, using molecular beam epitaxy. In order to understand the impact of Bi on the growth process, we have studied the influence of Bi addition to the growth and properties of GaN epilayers on sapphire substrate and GaN:Bi lateral epitaxial overgrowth (LEO) by metal organic vapor phase epitaxy (MOVPE). The gas phase Bi concentration was varied by changing the trimethyl bismuth/trimethyl gallium mole fraction from 0, 0.5%, 0.8%, 2.5% to 4.5% while keeping other growth parameters as constant. The growth rate of GaN:Bi epilayers on sapphire was found to be independent of Bi concentration over the range investigated. A significant improvement on the crystalline quality of GaN:Bi epilayers was observed as indicated by a narrow line width in both symmetrical and asymmetrical rocking curves by double-crystal x-ray diffraction. Low temperature photoluminescence of GaN:Bi showed additional emission peaks at 3.263eV and 3.179eV, which are attributed to the radiative recombination of an exciton bound to the Bi isoelectronic hole trap. Investigation of the surface morphology of the highly-Bi-doped GaN epilayers by atomic force microscopy (AFM) revealed a large number of surface depressions different from the more common dislocation-related surface pits often seen in MOVPE GaN. For GaN:Bi LEO growth, the lateral growth rate was increased and vertical growth rate was decreased at low Bi concentrations, while the lateral growth rate was reduced and vertical growth rate was enhanced at high Bi doping level.

G3.24
NONALLOYED Ti/Al OHMIC CONTACT TO N-TYPE GaN. H.W. Jang, C.M. Jeon, J.K. Kim, J-L. Lee, Dept of Materials Science and Engineering, Pohang University of Science and Engineering, Pohang, KOREA.

It is suggested that in Ti/Al bilayer contact to n-type GaN, low resistance Ohmic contact can be achieved by the creation of N vacancies, acting as a n-type donor with high temperature annealing. In case of p-type GaN, nonalloyed Ohmic contact has been demonstrated through the pretreatment by aqua regia solution. However, no works has been conducted on the nonalloyed n-GaN Ohmic contact. In the present work, nonalloyed Ti/Al Ohmic contact to n-GaN is obtained by surfaces etched by inductively coupled plasma (ICP) etching treatment. Cl_2 and BCl_3 are used as gas etchants. The typical etch rate was 480 nm/min. Ti/Al metal was deposited by an electron-beam evaporator with thickness of 30 and 300 nm, respectively. The contact resistance was measured using a circular transmission line model. Even without annealing, the specific contact resistance of Ti/Al metallization was $\sim 10^{-5} \Omega \cdot cm^2$ which is sufficiently low for the performance of high quality devices. In order to investigate the nonalloyed Ohmic mechanism, synchrotron radiation photoemission spectroscopy(SRPES), SIMS and high resolution TEM (HRTEM) will be employed. SRPES will show energy band banding by Fermi level shift for the Ohmic contact. In the etched n-GaN surfaces compared with non-etched surfaces, it is expected that Fermi level is shifted close to the conduction band minimum of GaN. From SIMS analysis, the Ga/N ratio distribution will be obtain from the compositional depth profile. Finally, the atomic structure and morphology of metal/GaN interfaces is studied by HRTEM. From these analysis, nonalloyed Ohmic contact mechanism will be revealed.

G3.25
THE EFFECT OF BUFFER LAYERS IN MOCVD GROWTH OF GaN FILM ON 3C-SiC/Si SUBSTRATE. C.I. Park[1], J.H. Kang[1], K.C. Kim[1], K.Y. Lim[1], E.-K. Suh[1] and K.S. Nahm[2]. [1]Department of Semiconductor Science and Technology; [2]School of Chemical Engineering and Technology, Semiconductor Physics Research Center, Chonbuk National University, KOREA.

The growth of GaN films on Si substrates is very attractive work because of irreplaceable merits of Si wafer such as low cost, high surface quality, large area wafer availability, high conductivity and well-established processing techniques. In this work, we studied the effect of buffer layers to grow high quality GaN films on 3C-SiC/Si(111) substrates. GaN films were grown on 3C-SiC/Si(111) by metalorganic chemical vapor deposition (MOCVD) using various buffer layers (GaN, AlN, and superlattice). The surface morphology and structural and optical properties of GaN films were investigated with atomic force microscopy (AFM), x-ray diffraction (XRD), Raman spectroscopy, and Photoluminescence (PL), respectively. GaN films grown using superlattice buffer layer showed only c-oriented (0002) plane of GaN from the XRD analysis. Raman spectra showed that the E_2 high mode agreed with the selection rule was well observed in all GaN films. The A_1(TO) and E_1(TO) mode were appeared for GaN grown without buffer layer, whereas the E_1(TO) mode was

additionally appeared in the GaN films grown with GaN buffer layer. In the PL spectra at low temperature, the peaks associated with band edge emission and donor-accepter pair (D^0A^0) were observed in GaN films grown without buffer layer or with GaN buffer layer and AlN buffer layer. GaN films grown with superlattice buffer layer showed band edge and very weak D^0A^0 emission. The root mean square (RMS) roughness of the GaN film grown on superlattice buffer layer was only 4.21 Å. Our experimental results indicated that the buffer layer affects crucially the qualities of GaN films grown on the 3C-SiC/Si substrate. Superlattice buffer layer improved the surface morphology as well as structural and optical properties of GaN films.

G3.26

EARLY STAGE GROWTH MODE OF GaN NUCLEATION LAYER ON SAPPHIRE(000L). C.C. Kim and J.H. Je, Synchrotron X-ray Laboratory (SXL), Department of Materials Science and Engineering, Pohang University of Science and Engineering, Pohang, KOREA; M.S. Yi and D.Y. Noh, Department of Materials Science and Engineering and Center for Electronic Materials Research, Kwangju Institute of Science and Technology, Kwangju, KOREA; F. Degave and P. Ruterana, Equipe Structure et Comportement Thermomecanique des Materiaux (CRISMAT UMR 6508 CNRS), Caen, FRANCE.

Since GaN device quality is strongly dependent on nucleation layer, many studies were tried to reveal the growth mode and control its microstructure. However the early stage growth has not been clearly understood yet mostly due to many structural defects induced by the large lattice mismatch (16%) with sapphire substrate. In this study, we investigated the early stage growth mode of GaN nucleation layer on sapphire(000l) using synchrotron x-ray scattering and high resolution transmission electron microscopy. We first reveal that deposited GaN nucleates islands alined with sapphire surface steps. Interestingly, the islands that have well-ordered cubic layer sequences are highly compressed in the film plane direction. The large compressive stress originates in coherent interface between GaN and sapphire. As growth proceeds, the large compressive stress gradually relaxes by generating misfit dislocations. Then it turns out that the stress finally reduces to small tensile state by 6/7 matching, wherein six-Ga atomic distances match to seven-Al atomic distances. As these layers contain very high densities of stacking faults, we suggest that the atomic migration at the interface caused by the large compressive stress can induces their formation, deteriorating the stacking order of nucleation layer. It is possible that this stress releasing mechanism might be applied to other hetero-epitaxial systems of large lattice mismatch as well.

G3.27

MOVPE GROWTH AND CHARACTERIZATION OF Si-DOPED CUBIC GaN. Fanghai Zhao, Jun Wu, Kentaro Onabe, Yasuhiro Shiraki, Univ. of Tokyo, Dept. of Applied Physics, Tokyo, JAPAN.

Cubic GaN can be obtained as a metastable phase by using cubic substrates under some suitable growth conditions. In fact, the growth of cubic GaN films on GaAs substrates has been much improved to give such samples that show good photoluminescence properties and stimulated emission with cubic AlGaN/GaN double heterostructures. Here, we report on the doping properties of cubic GaN, which are important for electronic and optoelectronic device applications. Cubic GaN films were grown by low-pressure (160 Torr) metalorganic vapor phase epitaxy (MOVPE) using trimethylgallium (TMG) and 1,1-dimethylhydrazine (DMHy) as the Ga and N precursors, respectively. Monomethylsilane (MMSi), diluted in ultra-pure hydrogen (10 ppm) was used as Si-doping source. GaN was grown using a two-step growth process. After the deposition of a 20 nm-thick buffer layer at 575C, Si-doped cubic GaN epitaxial layer was deposited at 900C. Such growth conditions as low V/III ratios and high growth temperatures were adopted to stabilize the cubic phase. Secondary ion mass spectroscopy (SIMS) measurements showed that with increasing MMSi flow from 0 to 18.4 nmol/min, the amount of incorporated Si varied by four orders of magnitude, exhibiting the high controllability of Si concentration. Optical properties of Si-doped cubic GaN were studied by using photoluminescence measurements. With increasing MMSi flow, generally observed excitonic emissions and donor-acceptor (DA) pair transitions shift to higher energies and broad in full width of half maximum (FWHM). Two peaks merge to one broad band when the MMSi molar flow exceeds 10 nmol/min. All the samples, including heavy-doped ones, did not exhibit emissions from hexagonal phase, showing that the high quality Si-doped cubic GaN films have been obtained.

G3.28

ATOMIC FORCE MICROSCOPE STUDY OF GaN GROWN ON Al_2O_3(0001) BY LP-MOCVD. K. Xu, D.H. Lim, B.L. Liu, X.L. Du, A. Yoshikawa, Center for Frontier Electronics & Photonics, Chiba Univ.-Venture Business Laboratory, Chiba, JAPAN; A.W. Jia, Chiba University, Dept. of Electronics & Mechanical Engineering, Chiba, JAPAN; K. Takahashi, Teikyo Univerity of Science and Technology, Department of Electronics and Information Science, Yamanashi, JAPAN.

There is currently a high degree of interest in understanding the diverse mechanisms that determine the growth morphology of epitaxial films. This understanding will greatly benefit optimization of both film growth and device fabrication. To understand and eventually control over these mechanisms, which directly affect the optelectronic properties of the epilayers, it is essential to know how the growth mechanisms are correlated with morphologies. In GaN MOVPE processes, growth temperature has a remarkable effect on the film morphologies and properties, but it is still not well understood. In present work, the temperature dependency of surface morphology of GaN epilayers grown by low-pressure metal-organic vapor phase epitaxy (LP-MOVPE) was studied using atomic force microscopy. It was demonstrated that dislocations strongly influence the growth mechanisms and the morphology of the films. Three growth modes were identified at different growth temperatures ranged from 1030°C to 1100°C, which are spiral growth dominated by dislocation with screw type, layer-by-layer growth dominated by dislocations with screw type, and nucleation-assisted step flow growth. The properties of GaN epilayers were closely related to the growth modes, which can be understood in the terms of impurity incorporation, and threading dislocation propagation that happened in different growth modes.

G3.29

GROWTH AND CHARACTERIZATION OF AlGaN/GaN 2DEG QUANTUM WELL STRUCTURES. A. Alam, B. Schineller, M. Heuken, and H. Juergensen, AIXTRON AG, Aachen, GERMANY; H. Hartdegen, P. Kordos, Forschungszentrum Juelich, ISI, Juelich, GERMANY.

AlGaN/GaN quantum well structures offer promising properties for applications such as high power and high temperature transistors which are capable of operating under caustic conditions. We investigated the growth of Si-doped and undoped AlGaN/GaN two dimensional electron gas (2DEG) structures grown on sapphire in an AIX 200 RF MOCVD system. The structures consisted of 2.7 μm thick GaN buffer layers grown on low temperature nucleation layers. The structures were capped with 28 nm thick AlGaN layers to generate the 2DEG at the AlGaN/GaN interfaces. The Al concentration was tuned between 17 and 27%. Typical growth temperatures for the structures of around 1,170°C and reactor total pressures of 50 to 200 mbar were employed. Typical growth rates of 2.5 μm/h and 0.6 μm/h were used for the GaN buffer and the AlGaN layer, respectively. The layers were then characterized by van-der-Pauw Hall measurements, low temperature photoluminescence (LTPL), atomic force microscopy (AFM) and Rutherford backscattering (RBS). For the undoped samples typical sheet carrier densities in the 2DEG of 3.5 x 10^{12} cm^{-2} were measured and electron mobilities of 7,500 cm^2/Vs, 6,500 cm^2/Vs and 1,350 cm^2/Vs were achieved at 10 K, 77 K and room temperature, respectively. Si-doped samples with a sheet carrier concentration of 7 x 10^{12} cm^{-2} exhibited electron mobilities of 1,250 cm^2/Vs. AFM measurements on these samples showed smooth surfaces with average roughnesses as low as 0.318 nm (RMS value), indicating excellent buffer layer qualities and AlGaN layer morphologies. 2.4 K LTPL measurements of the GaN buffer layers exhibit all three free excitons in spectra dominated by the B-exciton with a full width at half maximum of 2.4 meV. Additional data on homogeneities, electrical, optical and structural properties will be presented and correlated to the growth conditions.

G3.30

EFFECTS OF 6H-SiC SURFACE STRUCTURES ON AlN GROWTH MODE. Satoshi Yamada, Jun-ichi Kato, Satoru Tanaka, Ikuo Suemune, Research Institute for Electronic Science, Hokkaido University, Sapporo, JAPAN; Yoshinobu Aoyagi, The Institute of Physical and Chemical Research (RIKEN), Wako, JAPAN; Nobuaki Teraguchi, Akira Suzuki, Sharp Corporation, Tenri, JAPAN.

High quality AlN buffer layers on 6H-SiC substrates are the key to reduce defects in group III nitirde films. Especially, 6H-SiC surface structures such as step/terrace features affect the growth of GaN films. Commercially available 6H-SiC surfaces normally show many scratches and nano-meter scale roughness fluctuation. Recently, HCl/H_2 etching of 6H-SiC at ~1500°C was shown to be effective to improve surface quality. A clear periodic step feature was obtained [1]. It is expected that the defects in AlN and GaN films on such 6H-SiC surfaces can be reduced. In this report, we discuss the effects of 6H-SiC surface structures on AlN nucleation stages and defect formation mechanisms in AlN/6H-SiC. AlN films were grown on on-axis 6H-SiC (0001) substrates, which were etched by above mentioned etching process (etched 6H-SiC), by MOCVD. In comparison, AlN films on as-received 6H-SiC surfaces were also fabricated (un-etched 6H-SiC). Three-dimensional and two-dimensional nuclei were clearly observed by atomic force microscope (AFM) on un-etched and etched 6H-SiC surfaces,

respectively. This indicates that the growth mode was influenced by 6H-SiC surface structures. In addition, small pits were observed on AlN films grown on different 6H-SiC surfaces. These pits were present along steps on the AlN/etched 6H-SiC, while those were randomly distributed on the AlN/un-etched 6H-SiC. The density of the pits is smaller on the AlN/etched 6H-SiC than on the AlN/un-etched 6H-SiC. This indicates that the pits were originated in 6H-SiC surface steps. This is due to incomplete coalescence of AlN nucleus (kinetic issue) and the stacking mismatch between AlN and 6H-SiC at step edges [2]. The detailed formation mechanisms will be given by means of TEM analysis. [1] S. Nakamura et al, Appl. Phys. Lett. 76, 3412 (2000). [2] S. Tanaka et al., Appl. Phys. Lett. 66, 37 (1995).

G3.31
VAPOR PHASE SYNTHESIS AND CHARACTERIZATION OF GaN POWDER. Kazuhiko Hara, Yoshinori Matsuo, Yuuki Matsuno, Tokyo Institute of Technology, Imaging Science and Engineering Laboratory, Yokohama, JAPAN.

GaN-based materials have potential uses in powder phosphors for wide-area display devices because of their high luminescent efficiency and resistance to deterioration. For this purpose, we aim at synthesizing GaN powders with high crystalline quality as the matrix of phosphors. This paper describes preparation of undoped GaN powders by a novel method of vapor phase synthesis and their characterization.
The powder samples were synthesized by the reaction of a Ga vapor with ammonia in a chimney-type hot-wall reactor, 1 m long and 40 mm in inner diameter. Ga metal, placed at the inlet of a furnace, was vaporized at about 1280°C by rf induction heating. The generated vapor was transported to the hot zone of 900 - 1100°C by a N_2 carrier gas (0.5 slm), and mixed with a gas flow of ammonia (0.5 slm) and N_2 (0.5 slm). The as-synthesized sample was a mixture of GaN powder and Ga metal. Characterizations were carried out on samples from which Ga metal was removed chemically by hydrochloric acid. The particle size of synthesized GaN powders distributed typically from 0.2 to 2 μm in diameter.
It was found that the structural and luminescent properties depend strongly on the reaction temperature, T_r. The average diameter, d_{av}, increases with increasing T_r; e.g., d_{av}s of the samples synthesized at 900 and 1100°C were 0.6 and 1.4 μm, respectively. X-ray diffraction patterns for the samples synthesized at T_rs higher than 1050°C are characteristic of the wurtzite GaN, whereas those for the samples synthesized at lower than 1000°C indicate that the zinc-blende crystals are mixed in the powder. The samples show photoluminescence dominated by the band edge emissions at low and room temperatures. However, thermal quenching occurs significantly for the samples synthesized at lower T_rs, reflecting small d_{av}.

G3.32
EFFECT OF SUBSTRATE MISORIENTATION ON THE LATERAL EPITAXIAL OVERGROWTH OF GALLIUM NITRIDE. Cheolsoo Sone, Ok Hyun Nam, and Yongjo Park, Samsung Advanced Institute of Technology, Suwon, KOREA.

Lateral epitaxial overgrowth (LEO) techniques are widely used for reducing the dislocation densities in nitride semiconductors. This reduction of dislocation density is essentially required to reduce the compositional fluctuations of InGaN/InGaN multiple quantum well (MQW) and to realize a long lifetime InGaN/InGaN MQW laser diodes. It is well known that slight substrate misorientation is effective in obtaining a nitride epilayer with smooth surface. However there are no detailed experimental results on the effect of substrate misorientation on the LEO process. Firstly we have grown 2 um thick GaN template layers on (0001) sapphire substrates with different misorientation angle from 0.0 to 0.5 degree tilted toward $< 11-20 >$ directions using a low pressure metal organic chemical vapor deposition (LP-MOCVD) reactor. After the conventional oxide deposition, photolithography, and wet chemical etching, a stripe pattern of 4 um window and 10 um mask was defined in a direction of $< 1-100 >$. The growth parameters were chosen to obtain a completely coalesced microstructure to compare the surface morphology and the tilting angle between samples. As the misorientation angle increases to 0.1 degree, the surface morphology of the laterally epitaxial overgrown GaN layers becomes smooth. However further increase of the angle from 0.1 to 0.5 degree results in a deterioration of the GaN surface after LEO process. In addition to the surface morphology, the crystallographic tilting between two subgrains changed from a symmetric behavior into an asymmetric one with increasing misorientation angle. In this paper, we report the experimental results on the dependence of the LEO process on the substrate misorientation.

G3.33
STEP FLOW SURFACE MORPHOLOGY IN PLASMA ASSISTED MOLECULAR BEAM EPITAXY GROWN GaN. Kazuhide Kusakabe, Takayuki Yamada, Akihiko Kikuchi and Katsumi Kishino Sophia Univ, Dept of Electrical and Electronics Engineering Tokyo, JAPAN.

The step flow growth of GaN by plasma assisted molecular beam epitaxy (RF-MBE) was investigated. The step flow surface morphology of GaN is routinely obtained in metal organic chemical vapor deposition (MOCVD). In RF-MBE, however, the spiral hillocks of GaN predominantly arise due to a large driving force of spiral growth, even in the homoepitaxy on step-flowed GaN templates. And the spiral hillocks are correlated to the threading dislocations (TDs) with screw component. So to reduce the spiral hillocks, the suppressed TDs of screw character and/or the modification of MBE growth mode consider to be effective. In this study, two approaches were performed for realizing the step flow growth in RF-MBE GaN films, i.e. the insertion of AlN multiple interlayer (AlN-MIL) and the growth by migration-enhanced-epitaxy (MEE). The GaN layers were grown on MOCVD-GaN templates by RF-MBE. The combination-structure of AlN-MIL with 4 pairs of 8nm (above critical thickness) AlN and 5 pairs of 2nm (below critical thickness) AlN layers, respectively were grown on GaN templates followed by RF-MBE grown GaN. The AlN-MIL played a role for blocking TDs propagation from GaN templates. It was verified by atomic force microscope (AFM) that the step-flowed surface morphology was realized. This might be obtained because of reduced TDs with screw component by AlN-MIL. Next, GaN were grown with MEE mode, in which the surface migration of Ga-adatoms could be promoted. The step-flow growth was also appeared nevertheless no AlN-MIL was utilized. This result may show that the MEE mode enforces the step-flow growth to overcome spiral hillocks formation and that the thermodynamic system in MBE growth mechanism is modified by the alternative supply of nitrogen and Ga.

G3.34
AlN CRYSTAL GROWTH BY SUBLIMATION TECHNIQUE: MODELING AND EXPERIMENTAL STUDY. Alexey V. Kulik, Sergey Yu. Karpov, Alexander S. Segal, Soft-Impact Ltd., St. Petersburg, Russia; Mark S. Ramm, A.F. Ioffe Physical-Technical Inst, St. Petersburg, RUSSIA; Yuri N. Makarov, Fluid Mechanics Dept, Univ of Erlangen-Nuernberg, Erlangen, GERMANY; T. Hossain, M. Spencer, Howard Univ, Washington, DC.

Using a simple 1D model we show that aluminum and nitrogen are transported inside a growth cell jointly via convection and diffusion in AlN sublimation growth. Interplay between the two mechanisms is controlled by a proper choice of the vapor composition and pressure. The 1D model predicts existence of a critical pressure below which growth of AlN becomes impossible. 2D modeling of AlN growth shows that pressure variation near the critical value results in a drastic modification of the gas flow in the growth cell. Above the critical pressure species fluxes are directed from the AlN powder source to the seed. In contrast, below the critical pressure the reactive species go away both from the seed and source to the openings of the growth cell. Another important feature of the AlN sublimation growth is significant effect of N_2 adsorption kinetics on nitrogen incorporation into the crystal. We simulate the kinetic limitations using a temperature dependent nitrogen sticking coefficient extracted from the experimental data on free evaporation of AlN in vacuum. The kinetic effect leads under certain conditions to a non-monotonic dependence of the growth rate on temperature and pressure. At low pressures, growth rate is low because of the low nitrogen sticking probability. In contrast, at high pressure growth rate is suppresed due to low diffusivity of aluminum in the nitrogen atmosphere. These conclusions are supported by the experimental data obtained in parametric study of AlN growth. 1D and 2D modeling is applied to find conditions providing high growth rates of AlN crystal. The maximum growth rate is found as function of temperature and pressure. In particular, growth rate of about 1 mm/h can be achieved at temperature higher than 2250°C and at pressure higher than 1 atm.

G3.35
THERMAL STABILITY OF Si SUBSTRATES BONDED USING LOW MELTING POINT METALS AND ALLOYS. C.H. Wei, P.D. Moran, D.M. Hansen, T.F. Kuech, Dept of Chemical Engineering, University of Wisconsin, Madison, WI; S.E. Babcock, Materials Science and Engineering, University of Wisconsin, Madison, WI; G.W. Wicks, Institute of Optics, University of Rochester, Rochester, NY.

Wafer bonding of silicon has generally used SiO_2 as a bonding medium. The use of a low melting point metal allows bonding at both a low temperature as well as the possibility of utilizing the liquid metal as a stress-free bonding medium at elevated temperatures. We have investigated the use of In, Ti/Au/In and Al as bonding media for the formation of substrates in Si for GaN growth. The substrates consist of a thin Si layer of 0.1 to 2μm in thickness bonded to a handle wafer through the low melting point metal or metal alloy layer, often with a SiO_2 or Si_3N_4 layer between the upper Si layer and the metal as a diffusion or reaction barrier. This substrate would eliminate the thermal expansion mismatch induced stresses upon

cooling from the elevated GaN growth temperature by maintaining a stress-free bond between the growing layer, atop the thin Si template layer, and the underlying handle wafer. The fabrication of these metal-bonded substrates as well as their metallurgical and mechanical behavior at temperatures up to 1100°C will be presented. The interfacial energy between the metal and the Si substrate is a determining factor in maintaining a planar upper Si layer in the presence of mechanical and thermally-induced stresses. Indium-based bonding using SiO_2 reaction barriers were not stable at the elevated temperatures due to the high interfacial energy between the In and SiO_2. Al-based bonding without a SiO_2 reaction barrier layer against the handle wafer proved to be robust againest degradation allowing for temperature cycling to 1100°C.

G3.36
GROWTH OF GaN THIN FILMS BY THREE-STEP MOCVD METHOD. Seong-Woo Kim, Tomoki Shibata, Masahiro Akatsu, Toshimasa Suzuki, Nippon Inst of Technol, Saitama, JAPAN; Takashi Yamada, Kazuhiro Haga, Chichibu Fuji Co Ltd, Saitama, JAPAN.

Growth of GaN films on sapphire substrates with low-temperature (LT) GaN buffer layer changes from three-dimensional (3D) island growth mode to two-dimensional (2D) one. We applied three-step MOCVD method to improve the crystal quality of GaN thin films by optimizing the growth conditions for 3D stage and 2D stage separately. 2μm thick undoped-GaN films with 30nm thick LT- GaN buffer layer were grown in an EMCORE D-125 multi-wafer rotating disc low-pressure MOCVD system under reactor pressure of 200Torr. During MOCVD growth of GaN, "*in-situ*" photo-reflectance monitor enable us to know the transition of 3D/2D growth mode, i. e., reflectance traces change from 3D roughening stage without oscillation due to the development of individual islands, to quasi-2D growth stage with periodic reflectance oscillations, through recovery stage of the reflectance intensity as nucleation islands coalesce.
At first, we obtained the dependences of 3D/2D transition on V/III ratio and growth temperature. Reflectance traces in roughening and recovery stages significantly changed according to the V/III ratio and growth temperature. The higher the V/III ratio was and the lower the growth temperature was, the longer roughening stage and the slower recovery occurred.
Then we grew GaN films by three-step MOCVD method. Growth conditions for upper half GaN layer were fixed with V/III ratio of 2,500 and growth temperature of 1,030°C. Those for lower half layer (hereafter we call high-temperature (HT) buffer layer) were changed from 1,000 to 10,000 and from 1,000°C to 1,050°C, respectively. PL intensity of GaN film grown by three-step method with HT-buffer layer grown at 1,040°C became about 30% stronger than that grown by two-step method.
Three-step growth is effective to obtain high quality GaN films.

G3.37
INFLUENCE OF SAPPHIRE NITRIDATION ON PROPERTIES OF ZINC OXIDE GROWN BY RF SPUTTER DEPOSITION. S.-Q. Wang, A.J. Drehman, L.O. Bouthillette, K. Vaccaro, D. Schwall and P.W. Yip, Air Force Research Laboratory, Hanscom AFB, MA; Y.-B. Li, NZ Applied Technologies, Woburn, MA.

Zinc oxide is a wide band-gap semiconductor with high piezoelectric coefficient, birefringence, photoconductivity, transparency in the visible and infrared region as well as potential for light emission in the blue to ultraviolet range. In this paper we present a systematic study of the effects of the surface nitridation of (0001) sapphire substrates on the epitaxial growth of (0001) ZnO films of approximately 1.5 micron thickness grown by rf sputter deposition. We observed that the structure, optical and electrical properties of epitaxial ZnO were significantly influenced by the high temperature exposure of the sapphire substrate to ammonia, prior to the ZnO deposition. Varying the sapphire nitridation parameters strongly effected the out-of-plane and in-plane orientation and microstructures of the ZnO films. Using rocking curve measurements to estimate the dislocation densities we found that under the proper nitridation conditions the dislocation density can be reduced by a factor of 2 to 3, and this corresponded to a shorter, rather than longer, nitridation period of time. The photoluminescence behaviors as well as room temperature and low temperature electron transport characteristics of the ZnO films, including free carrier concentrations and electron mobilities, correlate with the structural results, which indicates that the nitridation of the sapphire substrate may be quite beneficial to the subsequent heteroepitaxy of high quality ZnO for optoelectronics applications.

G3.38
IMPACT OF ANNEALING ON THE STRUCTURAL PROPERTIES OF GaN AND AlGaN EPILAYERS. H. Heinke, V. Kirchner, T. Böttcher, S. Einfeldt, D. Hommel, H. Selke, University of Bremen, Institute of Solid State Physics, Bremen, GERMANY; T. Suski, M. Bockowski, High Pressure Research Center, Unipress, Warsaw, POLAND.

The paper focuses on the impact of thermal annealing on the structural properties of GaN based epitaxial layers. For this, single GaN layers as well as AlGaN/GaN heterostructures grown on c-plane sapphire were annealed in nitrogen atmosphere under different conditions (15 min at 1400°C and 13 kbar, or 20 min at 700 to 1050°C and 1 bar, respectively). Structural properties like strain state and defect structure of the as-grown and the annealed samples were studied both by X-ray diffraction and transmission electron microscopy (TEM). X-ray diffraction revealed a clear decrease in (001) rocking curve widths after annealing. This goes ahead with a broadening of (hkl) rocking curves if measured in asymmetric diffraction geometry. While these experimental data are in agreement with previous reports [1], they must not be interpreted aa an increase in twist of the mosaic blocks forming the imperfect epilayer. This is due to a clear change in shape of the reciprocal lattice points of the annealed layers pretending a deterioration of in-plane lattice properties. Indeed, (hkl) rocking curves measured in the more appropriate skew-symmetric diffraction geometry become much narrower after annealing. The concluded decrease in total dislocation density is supported by TEM results which show additionally voids in the layer and large regrown islands at the surface. Annealed single GaN layers exhibit larger biaxial compressive strain compared to the as-grown sample pointing to a direct correlation between dislocation density and strain state in this case. In contrast to that, annealing of AlGaN/GaN structures can enhance the relaxation of lattice misfit induced strain in the AlGaN layer. [1] J. Domagala et al., Thin Solid Films **350** (1999) 295.

G3.39
MASKLESS EPITAXIAL LATERAL OVERGROWTH OF GaN LAYERS ON STRUCTURED Si(111)-SUBSTRATES. A. Strittmatter, L. Reißmann, D. Bimberg, Technische Universität Berlin, Inst. f. Festkörperphysik, GERMANY, A. Dadgar, A. Krost, O.-v.-Guericke Univeristät Magdeburg, Inst. f. Exp. Physik, GERMANY.

Epitaxial lateral overgrowth of GaN has been achieved on structured Si(111) substrates in a single growth process starting from the nucleation layer. The substrates were structured in parallel stripes and trenches by a standard photolithography process followed by reactive ion etching. The orientation of these stripes were either parallel or normal to the $< 100 >$ direction. The growth is started by the deposition of an AlAs nucleation layer which is subsequently converted to AlN. Afterwards the GaN layers are grown for 10 min. (approx. 400 nm) with a V/III ratio of 1100 in order to get well defined sidewalls. Finally, the V/III ratio is changed to 3300 resulting in a lateral growth rate of about 2 μm per hour. Initially, the GaN layer grows both on the bottom of the trenches and on the top of the stripes, however, as soon as the lateral growth is enhanced by changing the V/III ratio, the GaN layer on top of the stripes grows preferentially in lateral direction at cost of the GaN layer growth on the bottom of the trenches. As a result, coalescence of the wings of laterally growing GaN can be achieved with sufficiently deep etched trenches. This process do not need any mask during growth nor growth interruption, therefore it is expected that the lateral overgrowth can be significantly improved.

G3.40
GROWTH MODE AND DEFECTS IN ALUMINUM NITRIDE SUBLIMATED ON (0001) 6H-SiC SUBSTRATES. Lianghong Liu, Bei Liu, Ying Shi, James H. Edgar, Dept. of Chemical Engineering, Kansas State University, Manhattan, KS.

Various (0001) 6H-SiC wafers were used as the substrates to study the sublimation growth of the AlN at 1800°C to 1900°C, including on-axis as-received, on-axis H2 etched, on-axis (0001) SiC with a 3C-SiC epitaxial layer, off-axis as-received, off-axis (0001)SiC with 6H-SiC epitaxial layer. The short and long-time growths for AlN sublimation indicate that the nucleation and growth depends on the substrates. The AlN sublimation layer on the off-axis 6H-SiC substrate with 6H-SiC epitaxy has the step flow growth mode in contrast to the island growth mode on all other substrates. Our theoretical analysis shows that the step height plays an important role in this mechanism. The bi-layer step height and step width of about 70 nm for the off-axis 6H-SiC substrate with 6H-SiC epitaxy results in the step-flow growth. Screw dislocations and cracks due to the lattice and mainly large expansion coefficient mismatch were always observed in the deposited AlN crystal, as characterized by SEM and optical microscopy. A theoretical model is presented to calculate the stress distribution in the heterostructure of AlN grown on 6H-SiC based on the thickness and the growth temperature. In addition, the sublimation of SiC seed at high temperatures is a main factor to degrading the AlN crystal quality and causing its island growth due to the roughing of the seed surface during initial furnace heating. An AlN buffer layer on the SiC substrate prepared by MOCVD before sublimation growth helps but does not change the growth mode.

G3.41
NUCLEATION OF GaN ON (0001) SAPPHIRE DURING MOCVD GROWTH: A HIGH RESOLUTION ELECTRON MICROSCOPY STUDY. F. Degave, P. Ruterana, G. Nouet, ESCTM-CRISMAT, Institut des Sciences de la Matiere et du Rayonnement, Caen, FRANCE; J.H. Je., C.C. Kim Department of Materials Science and Engineering, Pohang University of Science and Engineering, Pohang, KOREA.

An extensive HREM investigation is carried out on the early stage of growth of GaN on top of (0001) surface of sapphire. The growth was interrupted after 20′, 30′, 40′, 1min, 2min, 3min and 4min at 560°C. Then some of the layers were annealed at 1100°C and even growth of thick layers was undertaken. The analysis was made ex situ first by AFM in order to analyze the surface morphology and next by HREM in order to determine the interfacial relationships and fry to explain the growth mechanisms. Systematically, it was found that the thinnest layers are mainly defect free and have a cubic structure. The (001) planes are parallel to (0001) sapphire. As the thickness is increased the transformation to hexagonal strarts to take place and misoriented islands grow mainly in coalescence areas. During the annealing stage, the layer is found to completely transform to hexagonal and the misorientation is strongly decreased.

G3.42
IMPACT OF TWO-STEP MOVPE EPITAXIAL LATERAL OVERGROWTH OF GaN DIRECTLY IMAGED BY SCANNING CATHODOLUMINESCENCE MICROSCOPY. J. Christen, T. Riemann, Inst of Exp Physics, Otto-von-Guericke-University Magdeburg, GERMANY; B. Beaumont, P. Gibart, CRHEA-CNRS, Valbonne, FRANCE.

The impact of different growth methods on the evolution of epitaxial lateral overgrowth of GaN (ELOG) is comprehensively investigated applying spatially and spectrally resolved scanning cathodo-luminescence (CL) microscopy. A two-step MOVPE ELOG process is used: In the first step, a 2μm MOVPE buffer on sapphire substrate covered with a periodic mask of $Si_X N_Y$-stripes along [10$\bar{1}$0] was overgrown at 1080°C, favoring vertical growth. In the second step, a planar surface was achieved by either increasing the temperature up to 1120°C (sample A) or by introducing Mg into the vapor phase (sample B) [1]. The growth characteristics of the MOVPE ELO-GaN, exhibiting specific growth domains, are revealed by cross-sectional scanning CL microscopy. The coherently grown region between the mask stripes is always characterized by triangular areas of very low luminescence intensity, emitting both near bandgap CL and Yellow Luminescence. During the first growth step the onset of the lateral overgrowth, i.e. the transition from coherent (0001) growth to facet growth, is clearly marked by a general increase of luminescence intensity. For sample A, the onset of the second growth step is accompanied by an abrupt narrowing of the near bandgap peak, gradually increasing with advancing lateral overgrowth. In strong contrast, for sample B the second growth step resulted in a strong incorporation of impurities as evidenced by the appearance of a dominant donor-acceptor-pair recombination band restricted to the regions of off-facet lateral overgrowth. At about 6μm distance from the mask an abrupt transition of both luminescence intensity and lineshape is observed for both samples. Above this transition, up to the surface, clearly distinguishable sharp (FWHM<1.3meV) excitonic luminescence lines (i.e. FX, (D^0,X), ...) dominate the spectra both in between and on top of the mask stripes, proving excellent crystallographic quality. In plan-view CL wavelength images mapping the local emission energy over an area of 32μm x 22μm we find E_0=3.482eV (σ=0.42meV) and E_0=3.483eV (σ=0.67meV) for sample A and B, respectively. [1] P. Vennegues et al., JAP 87 (9), 4175 (2000)

G3.43
CORRELATION BETWEEN THE SIGN OF RESIDUAL STRESS AND N/Ga FLUX RATIO IN GaN FILMS GROWN BY RF-PLASMA ASSISTED MOLECULAR BEAM EPITAXY. A. Georgakilas, K. Amimer, M. Androulidaki, FORTH/IESL and Univ. Crete/Physics Dpt., Heraklion-Crete, GREECE; A.V. Sakharov and V. Yu. Davydov, Ioffe Physico-Technical Institute, St. Petersburg, RUSSIA.

Thin films of 0.70-0.95 micron thick GaN were grown on sapphire (0001) substrates by rf-plasma source MBE and examined by a variety of characterization techniques. The N/Ga ratio on the growing GaN surface was varied between strongly N-rich and slightly Ga-rich conditions in samples grown after the deposition and annealing of a 17nm thick AlN buffer layer. Samples with a thinner 5nm AlN buffer layer and a 20nm GaN buffer layer were also used to investigate any effects of the buffer layer type. The residual stress in the GaN films was estimated from the frequency shift of the E2(high) phonon line in room temperature Raman scattering spectra. It was found that the residual biaxial stress changed its sign from tensile to compressive as the growth conditions changed from N-rich to stoichiometric, for the samples with 17nm AlN buffer layers. The tensile stress was 0.5 GPa for N-rich growth and appeared almost independent from the exact value of the excess N-flux. Stoichiometric or slightly Ga-rich growth resulted to compressive stress up to 0.9GPa when a 17nm AlN buffer was used. The compressive stress was reduced to 0.2GPa for a 5nm AlN buffer and became zero in the sample grown with a GaN buffer layer. Photoluminescence measurements at 77K showed a systematic shift of the peak emission wavelength toward lower energies as the stress changed from compressive to tensile. Possible explanations of the results will be discussed.

G3.44
INTERACTION BETWEEN BASAL STACKING FAULTS AND PRISMATIC INVERSION DOMAIN BOUNDARIES IN GaN. Ph. Komninou, J. Kioseoglou, E. Sarigiannidou, G. Dimitrakopoulos, Th. Kehagias, Th. Karakostas, Aristotle University of Thessaloniki, Physics Department, Thessaloniki, GREECE; S. Mikroulis, A. Georgakilas, FORTH/IESL and University of Crete/Physics Department, Heraklion-Crete, GREECE; G. Nouet, P. Ruterana, ESCTM-CRISMAT, UMR6508-CNRS, ISMRA, Caen, FRANCE.

Stacking Faults (SFs) and Inversion Domain Boundaries (IDBs) are the dominant planar defects in thin films of GaN grown on (0001) sapphire substrates by rf-plasma source MBE. Different models of each type of defects exist: I1, I2, E stacking faults along with Holt and IDB* inversion domain boundaries. A detailed analysis of different interactions between these defects is presented. High-resolution electron microscopy (HREM) of cross-sectional specimen geometry, which gives images with resolution at the atomic scale, is used as experimental technique. The various atomic configurations of the expected models are constructed for the different interactions by means of the topological theory of defects. Such atomic structures provide the coordinates for the construction of HREM simulated images which are compared with the experimental ones.

G3.45
GROWTH OF QUATERNARY AlInGaN/GaN HETERO-STRUCTURES BY PLASMA INDUCED MOLECULAR BEAM EPITAXY WITH HIGH In CONCENTRATION. Alexanddre Pimenta Lima, Richard Tamas, Claudio R. Miskys, Oliver Ambacher, Martin Stutzmann, Walter Schottky Inst, Technical Univ of Munich, Garching, GERMANY; Axel Wenzel, Inst für Physik, Univ Augsburg, Augsburg, GERMANY; B. Rauschenbach, Inst für Oberflächenmodifizierung, Leipzig, GERMANY.

Theoretically, the growth control of the quaternary alloys AlInGaN allow the independent variation of the lattice constant and the band gap, opening the possibility for effective band gap engineering in a wide range. Besides, AlInGaN/GaN lattice matched structures allow the study and exploration of the strong piezoelectric effect and the spontaneous polarization present in III-V nitride layers. Nevertheless, the epitaxial growth of such layers is a very difficult task because Al-rich alloys require much higher growth temperatures than In-rich compounds. In the latter case, the growth temperature must be lowered in order to reduce the thermal dissociation of In-N bonds to increase the indium incorporation. AlInGaN films grown by MOCVD were already obtained by a few groups, where the alloy composition variation was obtained by means of changing the metal fluxes. However, In concentrations higher than 10% were difficult to achieve. The present work describes, for the first time, the growth conditions for AlInGaN by Plasma Induced Molecular Beam Epitaxy (PIMBE). We kept the flux of Ga, Al, and In as well as the nitrogen plasma conditions constant and varied the growth temperature from 650 to 775°C in order to achieve indium compositions varying from 4 to 15%. Reflection High Electron Energy Diffraction (RHEED) was used to monitor the quaternary growth. The structural quality and the lattice match of the AlInGaN/GaN heterostructures were verified by high resolution X-Ray diffraction ($\Theta/2\Theta$ and reciprocal space mapping), the alloy composition was determined by Rutherford Backscattering Spectroscopy (RBS). Results of Hall effect and capacitance-voltage (C-V) profiling of AlInGaN/GaN lattice matched and strained structures will also be presented.

G3.46
INVESTIGATION OF INITIAL GROWTH STAGE OF CUBIC-GaN USING AlGaAs BUFFER LAYER ON GaAs (100) BY MOLECULAR BEAM EPITAXY. Ryuhei Kimura and Kiyoshi Takahashi, Dept of Media Science, Teikyo University of Science and Technology, Uenohara, Kitatsuru-gun, Yamanashi, JAPAN.

Metastable cubic-GaN (b-GaN) is expected to have many advantages in physical properties over those of the hexagonal phase including lower resistivity, and higher doping efficiency due higher crystallographic symmetry. Cubic-GaN can be grown on GaAs, and the possibility of using GaAs substrates is one of the important pluses for device fabrication due to its ability to be easily cleaved. We have

demonstrated highly pure cubic-GaN epilayer growth using an AlGaAs buffer layer grown on GaAs (100) by molecular beam epitaxy. (1) In that work, there was one problem that the layer thickness of epilayer is only 0.4mm. In this work, detailed investigation of the initial growth condition which influence to phase purity of epilayer, and the dependence of layer thickness on the crystallinity were carried out. Plasma assisted molecular beam epitaxy was used for films growth using Si doped n-type GaAs (100). (2) By the three dimensional X-ray reciprocal space map measurement of the epilayer on a nitrided $Al_{0.17}Ga_{0.83}As$ buffer layer, we could not detect any peak attributed to hexagonal. These results indicate that the epilayer is the cubic (002) phase and does not contain any hexagonal phase. It was observed that the surface condition of AlGaAs bufer layer influences to the phase purity of epilayer. The surface, which was observed (4x1) reconstruction RHEED pattern which is thought As stabilized surface, leads to the high phase purity of epilayer, while the surface, which was observed (1x1) RHEED, leads to the mixing of hexagonal-phase at early growth stage. The mechanism of this effect and the dependence of layer thickness on the crystallinity are now underway. References (1) R. Kimura et al: Proc. of ICCBE-7, Tsukuba (1999) 103. Printed in a special issue of J. Crystal. Growth (1999). (2) R. Kimura et al: J. Crystal. Growth 189/190(1998) 406.

G3.47

MICROSTRUCTURE OF GaN FILMS GROWN BY RF-PLASMA ASSISTED MOLECULAR BEAM EPITAXY. Ph. Komninou, Th. Kehagias, Th. Karakostas, Aristotle University of Thessaloniki, Physics Department, Thessaloniki, GREECE; G. Nouet, P. Ruterana, ESCTM-CRISMAT, UMR6508-CNRS, ISMRA, Caen, FRANCE; K. Amimer, A. Georgakilas, FORTH/IESL and University of Crete/Physics Department, Heraklion-Crete, GREECE.

Thin films of GaN have been grown on sapphire (0001) substrates by rf-plasma source MBE. Samples corresponding both to N-rich and Ga-rich growth conditions of GaN were analyzed by conventional and high resolution TEM. All samples were characterized by high quality ~20nm AlN buffer layers grown in perfect epitaxial relationship with the Al_2O_3 substrate. Most of the threading dislocations started at the GaN/AlN interface while the inversion domain boundaries (IDBs) were starting from the AlN/Al_2O_3 interface. All the three types of basal stacking faults (SFs) were observed, i.e. I1, I2, E, while two types of IDBs were detected related to the Holt and the IDB* models. Some differences in the morphology and the defect content are observed between the N-rich and the Ga-rich growth conditions. In the N-rich samples the surface roughness is much higher than in the Ga-rich samples and high density of SFs near the free surface and just above the AlN/GaN interface is observed. In the Ga-rich samples the density of SFs is also high near the surface but low close to the AlN/GaN interface. IDBs are narrow and dense in the Ga-rich samples while wide IDBs are observed in N-rich samples.

G3.48

SOME CONSIDERATIONS ON THE GROWTH OF HIGHLY RESISTIVE GaN LAYERS. Z. Bougrioua, K. Jacobs, J. Cheyns, I. Moerman, Dept. INTEC, IMEC-Ghent University, BELGIUM; E.J. Thrush, Thomas Swan Scientific Equipment Ltd, Cambridge, UNITED KINGDOM; R H Wallis, R.A. Davies, Marconi Caswell Ltd, Northants, UNITED KINGOM.

Among the material related parameters that govern the performance of AlGaN-GaN Heterostructure Field Effect Transistors (HFET), the insulating character of the buffer layer is very challenging to control. This contribution focuses on the effort developed to find different ways to grow in a 3*2" close spaced rotating disk MOVPE reactor, highly resitive layers without losing the ability to grow afterwards nitride material with good crystalline quality. Here, four parameters are suspected to be effective in promoting the growth of highly resistive material, once combined properly: growth pressure, recrystallisation time of the nucleation layer, growth temperature and growth rate. An empirical phase diagram deduced from experience is proposed to define growth parameter regions that are potentially favourable to the growth of insulating GaN. Some characterisation techniques as TEM, SIMS, frequency dependent resistance, etc. are used to clarify the origin of the insulating character and to correlate it to the microstructure. The transfer of the specific insulating layer growth conditions, to the case of the growth of material with a significantly lower dislocation density (as using the ELOG technique or a growth technique at variable pressure) is not straightforward as the usage of certain parameters results in new problems. This point will be discussed. Finally, the quality and uniformity over 2" wafers of some highly resistive layers are evaluated through the characterisation of HFET devices.

G3.49

STRUCTURAL AND ELASTICITY-BASED PROPERTIES OF SiC-BASED INTERFACES: THEIR RELEVANCE TO THE HETEROEPITAXY OF 3-5 NITRIDES. Pierre Masri, Morad Rouhani Laridjani, Michel Averous, Groupe d'Etude des Semiconducteurs, CNRS-UMR 5650, Univ. Montpellier 2, Montpellier, FRANCE; Thomas Stauden, Jörg Pezoldt, TU Ilmenau, Institut für Festkörperelektronik, Ilmenau, GERMANY.

In the heteroepitaxy of 3-5 nitrides such as GaN and BN, a major problem concerns the choice of an optimized substrate. Usually, GaN is grown on sapphire substrates although these two materials present a large lattice mismatch (>12%) and BN films have been grown on several semiconductors as well as metallic substrates. For GaN heteroepitaxy, an alternative to sapphire substrates can be provided by SiC, which affords a better lattice matching and closer thermal expansion properties. For BN heteroepitaxy, a good choice of a substrate aiming at the fabrication of BN films with a very high percentage of the BN cubic phase (c-BN) is still under debate. Among several substrates, the choice of SiC for BN heteroepitaxy has led to BN films with a high percentage of c-BN. In this communication we present a methodology based on the elasticity theory of strained interfaces to optimize semiconductor heterointerfaces. In this approach, the optimization involves not only geometric parameters of host materials but also parameters related to their elastic properties which can be identified from the elasticity theory of solids. The basic physics of the theory correlates lattice dynamics and strain gradients via effective elastic constants associated with the host materials forming the heterosystem. For GaN/SiC, we predict a rather large mismatch for the dynamics-strain related factors and we show that the use of a AlN buffer layer can optimize the GaN/SiC heterointerface. In the case of BN, our approach enables us to discuss the physics of the c-BN composition of BN films grown on SiC substrate.

G3.50

Abstract Withdrawn.

G3.51

Abstract Withdrawn.

G3.52

STRAIN AND COMPOSITION ANALYSIS OF $In_xGa_{1-x}N$/GaN LAYERS. S. Pereira[a,c], M.R. Correia[a], E. Pereira[a], E. Alves[b], L.C. Alves[b], C. Trager-Cowan[c] and K.P. O'Donnell[c]; [a]Departamento de Fisica, Universidade de Aveiro, Aveiro, PORTGUAL; [b]I.T.N., Departamento de Fisica, Sacavem, PORTGUAL; [c]Department of Physics and Applied Physics, University of Strathclyde, Glasgow, Scotland, UNITED KINGDOM.

We report on strain and compositional properties of epitaxial single layers of nominally undoped wurtzite $In_xGa_{1-x}N$ ($0<x<0.25$) grown by MOCVD on top of GaN/Al_2O_3 substrates. Rutherford backscattering spectrometry (RBS) and particle induced X-ray emission (PIXE), were used to probe the indium content distribution with high depth (~5nm) and lateral (~2.5 micron x 4 micron) resolutions. RBS depth profiles allowed a direct observation of a compositional pulling effect in the most strained samples, revealing the tendency of In atoms to migrate to the surface, minimising the strain energy. We attempt to correlate the compositional variations with depth resolved cathodoluminescence(CL) measurements, highlighting the importance of this technique when studying InGaN/GaN heterostructures. The degradation of crystalline quality with increasing In content measured by RBS (comparing random and aligned backscattering yields) is shown to scale with the broadening of the optical absorption curves. RBS/channelling results combined with X-ray diffraction (XRD) measurements allowed the determination of both parallel and perpendicular strain components. $In_xGa_{1-x}N$ epilayers were found to be under tensile strain in the growth direction (0001) and under compressive strain in the direction parallel to the surface, this is in agreement with previous results [1]. We discuss the importance of considering the strain on the composition estimations, when XRD is used, as well as in the interpretation of optical characterisation results. [1] M.F. Wu, A. Vantomme, S.M. Hogg, G. Langouche, W. Van Der Stricht K. Jacobs and I. Moerman, Appl. Phys. Lett. 74, 365 (1999).

G3.53

MULTIPLE ZnO/C-ZnMgO SUPERLATTICE HETERO-STRUCTURES ON SAPPHIRE BY PULSED LASER DEPOSITION. Ajay Sharma, Alex Kvit, Jay Narayan, North Carolina State University, Dept of Materials Science and Engineering, Raleigh, NC; John Muth, C.W. Teng, Robert Kolbas, North Carolina State University, Dept of Electrical and Computer Engineering, Raleigh, NC.

We have recently synthesized single crystal cubic-$Zn_xMg_{1-x}O$ (c-ZnMgO) films with varying Zn content (x=0.0-0.18) by pulsed laser deposition (PLD). This wide-band gap alloy can be integrated with Si substrates and has potential applications in futuristic blue lasers or UV detectors. In the present work, we have used this alloy material as barrier layers to form multiple ZnO (0001)/ZnMgO (111) quantum

well structures on c-plane sapphire substrates. The characterization of these heterostructures was performed by X-ray diffraction (XRD), high resolution transmission electron microscopy (HRTEM), optical spectroscopy and photoluminescence (PL). We have performed Z-contrast imaging on these specimens to reveal the nature of interfaces and migration across the interfaces. The XRD results clearly revealed both ZnO (0001) and ZnMgO (111) type of reflections from the film. The optical transmission measurements revealed ZnO absorption-edge which was blue-shifted as a function of thickness of the well. The excitonic nature of the absorption-edge was clearly seen. The photoluminescence results showed a sharp PL peak which was blue-shifted from the corresponding excitonic band-edge of bulk ZnO. The c-ZnMgO being a stable alloy system as opposed to wurtzite phase, these results are encouraging from the point of view of phase-separation phenomenon observed by us in wurtzite system and by others in III-nitride system. The quantum confinement of carriers is thought to be responsible for the observed blue-shift.

G3.54
GROWTH OF BULK GaN CRYSTALS VIA VAPOR PHASE TRANSPORT. Hyunmin Shin, Raoul Schlesser, Zlatko Sitar and Robert Davis, North Carolina State University, Dept. of Materials Science & Engineering, Raleigh, NC.

Single crystalline gallium nitride crystals have been grown via vapor phase transport within a temperature range of 1050°C ~1200°C. Free-standing GaN crystals were grown on a BN surface by spontaneous nucleation utilizing a direct reaction of Ga with ammonia. Typically, direct reaction of Ga and NH_3 yields a large nucleation density, thus leading to smaller individual crystals. This problem has been overcome by introduction of a high temperature nucleation technique. The crystals grown by this technique were either needles or platelets depending on the process variables, i.e., growth temperature, reactor pressure and NH_3 flow rate, etc. The largest lateral and vertical growth rates (100μm/hr and 1mm/hr, respectively) were achieved under different growth conditions. Crystal quality was confirmed to be excellent by x-ray diffraction, Raman spectroscopy and scanning electron microscopy. Optimal growth conditions for lateral and vertical growth of GaN by this technique are presented in this paper.

G3.55
SURFACE ROUGHNESS, POLARITY AND STACKING FAULTS IN CUBIC GALLIUM NITRIDE EPILAYERS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION. B.Qu, S.F. Li, G.X. Hu, X.H. Zheng, Y.T. Wang, S.M. Lin, Hui Yang, J.W. Liang,Institute of Semiconductor, Chinese Academy of Sciences, Beijing, P.R. CHINA.

At present, the quality of cubic GaN is inferior to hexagonal GaN for its metastability. But cubic GaN with higher crystallographic symmetry has superior electronic properties and is easier to be doped or alloyed. The cubic wafer can also be cleaved easily in the device processing, which can be compatible with the GaAs-based devices. Recently, cubic GaN LEDs have been reported. The epitaxial surface of cubic GaN is always so rough that the optoelectronic properties are affected seriously and the devices fabrication become more difficult. In this paper, surface roughness was investigated by atomic force microscopy (AFM) and scanning electron microscopy (SEM). The surface roughness resulted from large amount of strips which prolonged in [110] or [-1-10] direction with small size in [1-10] or [-110] direction. Therefore, The surface fluctuations are more serious in [1-10] direction than in [110] direction. Transmission electron microscopy (TEM) indicated that the sidestep of each strip just was the top of high density stacking faults. Therefore, it is distributive polarity of stacking faults that is responsible to the surface roughness of cubic GaN epilayers. Since hexagonal inclusions and cubic microtwins are nucleated through stacking faults, their contents were measured in different X-ray incident directions with multifunction four-circle diffractometer. The results showed that the amount of hexagonal inclusions and cubic microtwins measured in [1-10] direction were twice or more as much as in [110] direction.

G3.56
OBSERVATION OF DISLOCATION ETCH PITS IN EPITAXIAL LATERAL OVERGROWTH GaN. T.C. Wen, S.C. Lee, C.H. Chiou, H.S. Chuang, W.I. Lee, Department of Electrophysics, and Microelectronics and Information Systems Research Center, National Chiao Tung University, HsinChu, Taiwan, REPUBLIC OF CHINA.

This work investigates dislocation etch pits in epitaxial lateral overgrowth (ELO) GaN by wet chemical etching. A mixture of H_2SO_4 and H_3PO_4 was used as a dislocation etchant, and SEM and AFM were employed to observe the surface topography. For the as-gown sample, SEM images present the flat, smooth surface without any pits or hillocks. After the chemical etching, hexagonal shaped etch pits were observed. At the edge of samples, a high densities of etch pits crowded at the "window" region. In contrast, the overgrowth region was nearly free of etch pits. Moreover, AFM observations for as-grown ELO GaN illustrate the undulating surface, which is due to the imperfect coalescence between the two overgrowth fronts. Three kinds of etch pits were observed in the widow region by AFM images. However, only large pits were observed at the overgrowth region. The origin of these etch pits at different regions are still unclear. Further investigations is required to identify these etch pits.

G3.57
CHARACTERIZATION OF LOW-DISLOCATION-DENSITY GaN FILMS FABRICATED BY ANTI-SURFACTANT MEDIATED EPITAXY. Misaichi Takeuchi[1], Satoru Tanaka[1,2], Hideki Hirayama[1] and Yoshinobu Aoyagi[1]. [1]The Institute of Physical and Chemical Research (RIKEN), Saitama, JAPAN; [2]Research Institute for Electronic Science, Hokkaido University, Sapporo, JAPAN.

Drastic reduction of the dislocation densities in GaN films has been succeeded by our sophisticated MOCVD growth procedure using anti-surfactant. The dislocation propagation is effectively terminated by anti-surfactant introduction. A co-worker, Tanaka reports the mechanism of the dislocation termination in another paper in this symposium [1]. Briefly, the dislocations are bent along the anti-surfactant-treated interface due to capping of the anti-surfactant on the dislocation sites, so that dislocation loops are generated within the anti-surfactant-treated interface. The dislocation-density reduction is accomplished on the whole wafer areas and is a function of the amount of the absorbed anti-surfactant. Therefore, characterization of our low-dislocation-density (LD) GaN films using some macro-area-evaluating techniques such as Hall measurement, V-I plotting, and so on become possible as a function of the dislocation densities. In this paper, we report the usefulness of our LD-GaN based on such characterization, and discuss how to optimize the growth conditions.
The growth details are the following. 0.5 μm-thick GaN buffer layers were deposited on AlN/6H-SiC(0001) substrates. After that, the growth sequence was interrupted to introduce the anti-surfactant. For the III-nitride, the anti-surfactant is Si, which was supplied with TESi. GaN overgrowth was consequently carried out on the anti-surfactant-treated GaN surfaces. The results of the small amount of the anti-surfactant introduction showed insufficient dislocation termination at the interfaces. However, the dislocation termination became more effective with increasing anti-surfactant amount, so that the dislocation densities were reduced to mid 10^7 cm^{-2}. For the optimization, controls of the anti-surfactant absorbed amount and its uniformity in the interfaces are most important key points. This is because the excess Si atoms have some harmful influences on the crystalline quality of the overgrown GaN layers.
[1] S. Tanaka et al., in this symposium.

G3.58
STRAIN RELAXATION AND ORDERING IN GaN/AlGaN MULTIQUANTUMWELLS. A. Dadgar, J. Bläsing, P. Veit, A. Diez, F. Bertram, J. Christen, and A. Krost, Otto-von-Guericke Universität Magdeburg, Fakultät für Naturwissenschaften, Magdeburg, GERMANY; A. Alam and M. Heuken, AIXTRON AG, Aachen, GERMANY.

Group-III nitrides play an important role for light emitting devices in the green to ultraviolet (UV) region. Green and blue light emitters have been commercialized in the past years but light emitters in the UV are still not available. For the UV region GaN/AlGaN and AlGaN/AlGaN quantumwells are needed. We investigated MOCVD grown GaN/AlGaN multiquantumwells (MQW) with different Al content. In high resolution reciprocal space map X-ray measurements around the (0002) reflection samples show satellite peaks in the q_x-direction. These satellite peaks which have decreasing intensities with lower Al content are arranged symmetrically around the superlattice peaks in q_z direction. The distance of the satellite peaks corresponds to an in-plane periodicity around 16 nm. In asymmetric reciprocal space maps around the $(10\bar{1}4)$, $(20\bar{2}4)$ and $(20\bar{2}5)$ reflections the satellite peaks shift towards lower q_x values, indicating a partial relaxation in the a-lattice plane. We conclude that the AlGaN barrier induced strain in the GaN layer leads to the formation of quantum dot like tensile and compressively strained regions with a periodicity around 16 nm. Integral cathodoluminescence (CL) spectra averaged over a surface area of 14 μm x 9 μm exhibit broad (FWHM >145 meV), however very bright emission lines from GaN MQW islands with both, compressive and tensile strain centered at 3.521 eV and 3.333 eV, respectively in addition to the AlGaN buffer luminescence at around 4.18 eV. Highly spatially resolved CL directly visualizes the different microscopic origin of both lines strongly correlated to the surface morphology and the decomposition of the broad GaN MQW luminescence into sharp local spectra of FWHM <38 meV and peak energies varying on a nanometer length scale.

G3.59
DIRECT OBSERVATION OF BULK AND INTERFACE STATES IN GaN ON SAPPHIRE GROWN BY HYDRIDE VAPOR PHASE EPITAXY. Stephen H. Goss, Leonard J. Brillson, Ohio State Univ, Center of Materials Research, Columbus, OH; David C. Look, Wright State Univ. Dayton, OH; Richard J. Molnar, Massachusetts Institute of Tech, Lincoln Labs, Lexington, MA.

We have analyzed GaN grown by hydride vapor phase epitaxy on sapphire to identify defect states and their distribution across these materials. We used imaging cathodoluminescence (CL) spectroscopy to analyze and compare samples with different interface carrier concentrations and their physical origin. In each case, we observed several defect states including: a "blue" defect at 420 nm (2.9 eV) whose intensity peaks at the GaN-sapphire interface, a UV defect at 326 nm originating within the sapphire, a 560 nm "yellow" luminescence, as well as bright and dark band edge luminescent regions varying across the interface and bulk. Interface-specific spectra from each of the specimens showed that the peak intensity of "blue" GaN emission follows the carrier concentration at the interface over two orders of magnitude. This correlation, along with corresponding SIMS results identifying diffusion of the substrate across the interface strongly indicates that the carrier concentration is caused by impurities from the sapphire substrate. Furthermore, cross sectional mapping studies revealed strongly luminescent GaN band edge states at the GaN-sapphire interface, corresponding to the highly conducting degenerate n-type interface region found by Hall-effect measurements. This enhanced band edge emission may result from increased shallow donors due to point defects, impurities, or extended defects in the material at the interface. Work is now underway to probe the near band edge region at low temperature to identify spatial distributions of shallow donors in the GaN films and to further characterize the degenerate region spatially. This work is supported by the Office of Naval Research (Colin Wood).

G3.60
STRAIN RELAXATION IN GaN EPITAXIAL LATERAL OVERGROWTH ON SILICON SUBSTRATE. Q.K.K. Liu, Hahn-Meitner-Institut, Berlin, GERMANY; T. Riemann, J. Christen, Otto-von-Guericke-Universität, Magdeburg, GERMANY; A. Kaschner, A. Hoffmann, C. Thomsen, TU Berlin, Berlin, GERMANY; K. Hiramatsu, Mie University, Mie, JAPAN.

The strain relaxation in two kinds of GaN epitaxial lateral overgrowth structure (ELOG) on Si(111) substrates are investigated theoretically, using the continuum theory simulated by the finite-element method. The two different structures resulted from the circular and stripe SiO_2-mask patterns through which they were grown. The former yielded hexagonal pyramids while the latter facetted stripes with triangular cross-sections. Using scanning cathodoluminescence spectroscopy we have observed fully relaxed GaN at the peaks of both ELOG. However, the blueshifts along the pyramid surfaces are in contrast to the redshifts from the facetted stripes. The correlation between the results from scanning cathodoluminescence spectroscopy on the one hand and micro-Raman spectroscopy and theoretical modelling of the strain relaxation on the other have been investigated.

SESSION G4: DOPANTS AND PROCESSING
Chairs: James S. Speck and Tsvetanka S. Zheleva
Tuesday Morning, November 28, 2000
Room 210 (Hynes)

8:30 AM *G4.1
THE ROLE OF OXYGEN DOPING IN THE NITRIDES. B.K. Meyer, D.M. Hofmann, F.H. Leiter, and H. Alves, I. Physics Institute, Justus Liebig University Giessen, Giessen, GERMANY.

Although the quality of III-Nitride epitaxial films have considerably improved in the recent years there are still open questions about the nature of residual shallow impurities and deep defects, and especially those which are introduced by doping (compensating centres). Oxygen causes a major influence on the properties of the AlGaN alloy system, and was from the early years of nitride epitaxy considered to be the origin of the n-type conductivity in autodoped GaN films. We review the results obtained on GaN:O by high pressure experiments, and then report on a comprehensive quantitative identification of the shallow oxygen donor in GaN by a correlation of Hall effect and SIMS measurements. Oxygen is also involved in the deep recombination bands at 2.2 and 1.8 eV. We compare the defects which are detected by optically detected magnetic resonance (ODMR) in the yellow and red emissions in undoped GaN and point out the similarities to the deep donors in GaN:Mg. The compensating centres are most likely vacancy-type complexes.

9:00 AM G4.2
OPTICAL AND ELECTRICAL PROPERTIES OF Be DOPED GaN BULK CRYSTALS. T. Suski, E. Litwin-Staszewska, P. Perlin, P. Wisniewski, H. Teisseyre, I. Grzegory, M. Bockowski and S. Porowski, High Pressure Research Center, UNIPRESS, Warsaw, POLAND; K. Saarinen and J. Nissila Laboratory of Physics, Helsinki University of Technology, Espoo, FINLAND.

Berylium, replacing Ga in GaN is one of the most promising candidates for the effective acceptor. In this work we concentrate on studies of physical properties of Be doped bulk GaN crystals and on comparison of their properties with bulk GaN:Mg. Bulk GaN crystals grown under high Nitrogen pressure, if undoped, are always conducting with electron concentration in the range of $5x10^{19}$ cm^{-3}. Oxygen impurity seems to be the main source of donors. Growth procedure based on the high pressure synthesis from the solution in liquid Ga containing of Be leads to either n-type material (low amount of Be) or to highly resistive crystals (high concentration of Be). These effects suggest an importance of the compensation of Be acceptors by O donors and resembles situation typical for Mg doped bulk GaN crystals. The role of Be interstitials (Bei donors) important for compensation in oxygen free epitaxial growth of GaN:Be, is less probable here since its formation energy is higher than that corresponding to substitutional oxygen, ON. Additionally, the both types of highly resistive crystals, GaN:Mg and GaN:Be show a significant red shift of the optical absorption edge suggesting importance of a impurity band formation/potential fluctuations effects. Highly resistive GaN:Be exhibits some unexpected features, very different from that observed in highly resistive bulk GaN:Mg. In particular, up to 300 K strong yellow band, YB, dominates photoluminescence spectrum in resistive GaN:Be crystals. Moreover, positron annihilation studies point out the presence of gallium vacancies, V_{Ga}. It is difficult to understand these findings within the present knowledge. In highly resistive GaN:Mg neither YB nor detectable concentration of V_{Ga} was found. Additionally, for a conducting bulk GaN the correlation between YL intensity and concetration of V_{Ga} was elucidated and this observation is in agreement with thermodynamical calculations showing low formation energy of Ga-vacancy in a material with high value of the Fermi level only (n-GaN). We will discuss these puzzling effects in bulk GaN:Be in terms of contributions caused by different dopants/native defects and codoping phenomena.

9:15 AM G4.3
STABILITY AND DIFFUSION OF BERYLLIUM IN WURTZITE GaN. Sukit Limpijumnong and Chris G. Van de Walle, Xerox PARC, Palo Alto, CA; Jörg Neugebauer, Fritz-Haber-Institut, Berlin, GERMANY.

In the quest for a p-type dopant in GaN, Be might be a better choice than the currently used Mg. Indeed, our calculations indicate that the substitutional Be acceptor (Be_{Ga}) exhibits a lower ionization energy and a higher solubility than Mg. However, we find that compensation may occur due to incorporation of Be interstitials (Be_{int}), which act as donors. In bulk GaN, the formation energy of Be_{int} is comparable to that of Be_{Ga}, hence incorporation is likely. We have performed a comprehensive first-principles study aimed at assessing to what extent Be interstitials will form, and whether they could be removed from the p-type layer. For that purpose we have mapped out the complete total-energy surface for Be_{int}. We use density-functional theory in the local density approximation, and norm-conserving pseudopotentials. Supercells ranging from 32 to 96 atoms in size were used. We obtain a highly anisotropic diffusion barrier: the activation energy for migration parallel to the c-axis is 2.9 eV, while perpendicular to the c-axis it is only 0.9 eV. The atomistic origins of this anisotropy will be discussed. We have also studied Be_{int}-Be_{Ga} complexes, which can form with a binding energy of 1.3 eV. Consequences of these results for experiments involving Be will be discussed.
This work is supported by ONR under contract #N00014-99-C-0161.

9:30 AM G4.4
DISLOCATION ELECTRICAL ACTIVITY IN AlGaN/GaN HETEROSTRUCTURES. D.V. Lang, M. Manfra, J.W.P. Hsu, S. Richter, A.M. Sergent, R.N. Kleiman and L.N. Pfeiffer, Bell Labs, Lucent Technologies, Murray Hill, NJ; R.J. Molnar, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, MA.

In this work, the effect of dislocations on the leakage across the AlGaN barrier in AlGaN/GaN heterostructures is investigated using conventional I-V measurements and scanning probe techniques. The 0.6 μm AlGaN/GaN heterostructures are grown by MBE on thick ($\approx 20\mu$m) HVPE GaN templates. The dislocation density is $\approx 5x10^8$ cm^{-2}, determined by the HVPE templates. The mobility of the 2D electron gas is above 10,000 cm^2/Vsec at low temperatures and the sheet density is in the mid-10^{12} cm^{-2}, both depending on AlGaN barrier thickness and composition. C-V measurments show that N_D-N_A is as low as mid-10^{14} cm^{-3} in the undoped MBE GaN layers.

On the whole, the MBE growth replicates the surface morphology of the HVPE film, with monolayer steps clearly visible in topographic images. However, the surface morphology near dislocations depends strongly on the MBE growth conditions. Under Ga rich growth the dislocations appear as bumps, while under stoichmetric growth they appear as pits. Scanning Kelvin probe microscopy reveal that these pits have a larger surface potential than the surrounding areas, consistent with a local excess of negative charge. The Ga rich surfaces show no nanometer scale surface potential variations, but scanning current-voltage images show that the dislocations are leaky under reverse bias. We also find that above bandgap UV light can significantly change the I-V characteristics of these heterostructures. The effect is reversible but with a long time constant and a strong bias dependence.

9:45 AM G4.5
CARRIER RECOMBINATION AT DISLOCATION IN INDENTED GaN SINGLE CRYSTALS. M. Albrecht, H.P. Strunk, Universität Erlangen-Nürnberg, Institut für Werkstoffwissenschaften, Mikrocharakterisierung, Erlangen, GERMANY; J.L. Weyher, University of Nijmegen, RIM, Experimental Solid State Physics III, Nijmegen, NETHERLANDS; I. Grzegory, S. Porowski, High Pressure Research Centre, Polish Academy of Sciences, Warsaw, POLAND; T. Wosinski, Institute of Physics, Polish Academy of Sciences, Warsaw, POLAND.

It is now well a well established fact that dislocations act as nonradiative recombination centres in group III-nitride based devices. However, up to now no systematic study exist that directly correlates the structure of extended defects in group III-nitrides to their electrical/optical properties. We in this paper analyse by means of transmission electron microscopy carrier recombination at dislocation that are induced by indentation into dislocation free GaN single-crystals. We deform dislocation-free ($<10 cm^{-2}$) GaN single-crystals with a Vickers diamond indenter at 370°C. Defect etching of these indented samples with a molten KOH-NaOH eutectic at 200°C reveals individual dislocations in the form of etch pits. From transmission electron microscopy we obtain three main results: (i) Dislocation (b=1/3<11-20) form and glide exclusively on polar (0001) and {10-11} glide planes. These results in a dislocation network in the (0001) plane formed by screw and 60° dislocations ($b=1/3< 11-20 >$, (ii) mutual intersection of screw dislocations during glide induces kinks on the dislocation lines, (iii) kinks either pin the dislocations or induce point defects (vacancies/Interstitial pairs) upon glide. Spatially and spectrally resloved cathodo-luminescence performed in the scanning transmission electron microscope shows radiative and nonradiative transistions at dislocations. Radiative recombination is observed at 2.4 eV, 2.9 eV and 3.2 eV. We analyse by high resolution transmission electron microscopy the core structure of these dislocations and discuss the origin of the recombination centres.

10:30 AM G4.6
IDENTIFICATION AND THERMAL STABILITY OF Ga VACANCIES IN ELECTRON-IRRADIATED Mg-DOPED GaN BULK CRYSTALS. K. Saarinen, J. Nissila, Laboratory of Physics, Helsinki University of Technology, FINLAND; T. Suski, I. Grzegory, UNIPRESS, High Pressure Research Center, Polish Academy of Sciences, Warsaw, POLAND; D.C. Look, Semiconductor Research Center, Wright State University, Dayton, OH.

Previous positron annihilation experiments [1-3] have shown that negative Ga vacancies are formed during the growth of n-type GaN bulk crystals and epitaxial layers. In semi-insulating Mg-doped GaN crystals, however, these vacancies are not present, most likely due to their large formation energy [4,5]. In this work we have applied positron spectroscopy to study the introduction of vacancies in Mg-doped bulk GaN crystals irradiated with 2 MeV electrons to the fluences $(3\text{-}10)\times10^{17} cm^{-2}$ at 300 K. The increase of the average positron lifetime by 3 - 6 ps gives direct evidence of the introduction of vacancy defects in electron irradiation. The decomposition of the lifetime spectra yields a positron lifetime of 235 ps for the irradiation-induced vacancy. This lifetime is close to that estimated for the Ga vacancy in calculations [1,3], but it is much longer than expected for the N vacancy. Furthermore, the lifetime of 235 ps is the same as observed previously for native Ga vacancies in n-type GaN [1-3]. The irradiation-induced defect can thus be positively identified as Ga vacancy or a complex involving V_{Ga}. Nitrogen vacancies are probably also produced by the irradiation, but in semi-insulating GaN they are positively charged and thus not seen in positron experiments [4,5]. Isothermal annealing experiments indicate that the irradiation-induced Ga vacancies recover in 30 min heat treatments at 500 - 600 K. [1] K. Saarinen et al., Phys. Rev. Lett. 79, 3030 (1997). [2] K. Saarinen et al., Appl. Phys. Lett. 73, 3253 (1998). [3] K. Saarinen et al., Physica B 273 - 274, 33 (1999). [4] J. Neugebauer and C.G. Van de Walle, Appl. Phys. Lett. 69, 503 (1996). [5] T. Mattila and R.M. Nieminen, Phys. Rev. B 55, 9571 (1997).

10:45 AM *G4.7
TRANSFER OF NITRIDE DEVICE HETEROSTRUCTURES FROM SAPPHIRE GROWTH SUBSTRATES TO SILICON BY METAL BONDING AND LASER LIFT-OFF. T. Sands, W.S. Wong[a], L. Tsakalakos, A. Salleo, Y. Cho, N. Quitoriano, University of California, Berkeley, Dept of Materials Science & Engineering; N.W. Cheung, University of California, Berkeley, Dept of Electrical Engineering & Computer Sciences ([a]now at Xerox Palo Alto Research Center).

Although sapphire has proven to be a suitable substrate for the growth of device-quality (Al,Ga,In)N heterostructures, the thermal, electrical and mechanical properties of sapphire limit the performance and complicate the fabrication of light-emitting and laser diodes. Furthermore, the high growth temperatures required for nitride CVD preclude direct integration with other less robust classes of materials (e.g., CMOS silicon, glass and polymers). Among the envisioned integrated devices that would be enabled by a more versatile integration scheme are nitride LEDs on low-cost flexible substrates, bioassay arrays based on fluorescence excitation and detection in microfluidic systems, and low-mass thin-film laser diodes for optical information retrieval. The authors along with their industrial collaborators at Xerox PARC have recently demonstrated that LED heterostructures may be transferred from sapphire to silicon without degradation in the electroluminescence and I-V characteristics. This "paste-and-cut" process combines Pd-In transient-liquid-phase (TLP) metal bonding with excimer laser lift-off (LLO) to transfer device heterostructures, including one or both ohmic contacts, to a receptor substrate without heating the receptor substrate above 200°C. In this talk, the factors in the optical, thermochemical and thermomechanical design of the TLP/LLO process that influence yield will be discussed. In particular, the control of the Pd-In reaction kinetics, the importance of acoustic impedance matching, and the role of the optical quality of the sapphire substrate will be emphasized.

11:15 AM G4.8
LOW RESISTANCE OPTICALLY TRANSPARENT CONTACTS TO P-TYPE GaN USING OXIDIZED Ni/Au AND ITO FOR LED APPLICATION. D.L. Hibbard, C.H. Lin, H.P. Lee, Univ. of Calif., Irvine, Dept of Electrical and Computer Engineering; Z.J. Dong, F.J. Szalkowski, J. Chen, C. Chen, Alpha Photonics-AXT.

Due to high resistance in the p-GaN cap layer, GaN based LEDs require a current spreading layer (CSL) to achieve uniform luminescence. The CSL must exhibit low sheet resistance, low contact resistance, R_c, with p-GaN, and high optical transparency. Improvement in the CSL can fundamentally enhance the performance of GaN-based LEDs. Recent reports on oxidized Ni/Au (NiO/Au) and indium tin oxide (ITO) contacts offer new options for this layer. The NiO/Au contacts formed by oxidizing a thin bilayer of Ni/Au under air or water vapor have shown record low levels of R_c while increasing transparency [1]. However, the best performing of these layers may be too thin to accommodate the anticipated current density for high power applications. Conversely, ITO films have demonstrated good current spreading and excellent transparency but suffer from high R_c with p-GaN. Operating voltages of over 7 V are reported at 20 mA, compared to less than 4 V for similar devices with conventional Ni/Au contacts [2]. In this paper, we describe a novel combination of these two approaches in which an 8 nm NiO/Au layer is created on the p-GaN surface using a method similar to Ref. 1. The sample is then overcoated by a 200 nm ITO film using reactive sputtering. The NiO/Au layer shows an R_c of $1.8\text{x}10^{-3}$ Ω-cm^2 that is nearly 10 times lower than conventional Ni/Au annealed under N_2. Measurements on fully processed LEDs with a NiO/Au/ITO CSL show an operating voltage of 4 V at 20 mA and a series resistance of 40 Ω. These results are comparable to LEDs fabricated with conventional Ni/Au and a dramatic improvement over the previous ITO data [2]. Process optimization is expected to further lower the operating voltage. These results demonstrate the feasibility of using NiO/Au/ITO as a CSL for high performance GaN LEDs. References: 1. J.-K. Ho, C.-S. Jong, C.C. Chiu, C.-N. Huang, and K.-K. Shih, J. Appl. Phys., 86, 4491, (1999). 2. T. Margalith, O. Buchinsky, D.A. Cohen, A.C. Abare, M. Hansen, S.P. DenBaars, and L.A. Coldren, Appl. Phys. Lett., 74, 3930, (1999).

11:30 AM G4.9
EVIDENCE FOR THE IMPACT OF POINT DEFECTS ON N-GaN LEDS VIA DEEP LEVEL GENERATION. A. Hierro, J.J. Boeckl and S.A. Ringel, Dept. of Electrical Engineering, The Ohio State University, Columbus, OH; M. Hansen, L. Zhao, J.S. Speck, U.K. Mishra, and S.P. DenBaars, Materials and Electrical and Computer Engineering Depts, University of California, Santa Barbara, CA.

While the role of extended defects in n-GaN optoelectronic devices has been studied in some detail, to date little is known regarding the effect that point defects may have on such devices, and for which deep levels they are responsible. We have used a combination of deep level optical spectroscopy (DLOS) and deep level transient spectroscopy

(DLTS) to probe levels throughout the entire bandgap in MOCVD-grown n-GaN. In addition, post-growth hydrogenation, electron beam induced current microscopy (EBIC) and transmission electron microscopy (TEM) have been used to identify the physical sources for the deep levels. Two sets of structures (A and B) each comprising of an LED and a test sample (designed for DLOS/DLTS) are used for this study. Both test sample A and B show deep levels at Ec-Et=0.60, 1.35, 2.64-2.80, and 3.22 eV, but with very different concentrations: 2.7×10^{14}, 5.0×10^{14}, 6.6×10^{14} and 1.0×10^{15} cm^{-3}, for A, and 4×10^{14}, 2.1×10^{16}, 2.7×10^{16} and 3.5×10^{16} cm^{-3} for B, respectively. Moreover, LED B shows a large decrease in light emission compared to A, while the threading dislocation (TD) density from TEM analysis remains constant ($\sim4\times10^{18}$ cm^{-2}). EBIC analysis gives a similar TD density and shows that the electrical activity of the TDs remains unchanged between samples. This all indicates that the Ec-Et=1.35, 2.64-2.80 and 3.22 eV deep levels are most likely generated by point defects, and can account for the decrease in device efficiency from LED A to B. Post-growth hydrogenation of sample B also shows drastic H-passivation of the 0.60 and 1.35 eV levels, whose concentrations decrease by over an order of magnitude, but no changes in the electrical activity of TDs are observed. These results further support the point defect origin for the 0.60 and 1.35 eV levels. The role of TDs in deep level generation will be addressed by means of a comparison of LEO vs. dislocated n-GaN.

11:45 AM G4.10
POROUS GaN FABRICATION AND APPLICATION IN DOPING ENHANCEMENT AND STRAIN RELAXATION IN EPITAXIAL GROWTH. X. Li, I. Adesida, and P.W. Bohn, University of Illinois, Urbana, IL.

We explore the use of porous GaN, PGaN, as a buffer layer, or an intermediate layer, in III-nitride growth for two purposes. First, using the porous structure as a sink for mismatch dislocations, PGaN or PSiC buffer layers will likely permit the growth of low strain, low dislocation density GaN films. Secondly, the large surface area of PGaN presents unique opportunities to produce high p-type doping. We present porous GaN fabricated by a novel metal-assisted chemical etching method and by anodic etching under UV illumination. The morphology and optical properties of the porous GaN fabricated under a variety of etching parameters are characterized extensively using scanning electron microscopy, cathodoluminescence, Raman and photoluminescence spectroscopy. The optimum porosity of the porous GaN layer or multilayers for application as a compliant substrate and for enhanced doping will be discussed.

SESSION G5: LATERAL EPITAXY AND GROWTH
Chairs: Kazumasa Hiramatsu and Randall M. Feenstra
Tuesday Afternoon, November 28, 2000
Room 210 (Hynes)

1:30 PM *G5.1
APPROACHES FOR REDUCTION OF THE DEFECT DENSITY IN GROUP III - NITRIDE BASED HETEROSTRUCTURES.
T.S. Zheleva[1,2], W. Ashmawi[2], R.D. Vispute[3], and K.A. Jones[1]; [1]Sensors and Electron Devices Directorate, US Army Research Laboratory, Adelphi, MD; [2]North Carolina State University, Raleigh, NC; [3]Department of Physics, University of Maryland, College Park, MD.

Lateral epitaxial overgrowth (LEO), pendeo-epitaxy (PE) and solid phase epitaxial recrystallization (SPER) will be discussed as three approaches for reduction of the defect density in group III-nitride based heterostructures. The increased interest in the phenomenon of lateral epitaxy in the past few years is mainly due to the four-to-five orders of magnitude reduction of the dislocation density in the regions of lateral epitaxial overgrowth (LEO), compared to the regions of conventional vertical growth. Lateral epitaxy is observed in GaN structures grown selectively via MOCVD on 6H-SiC, as well as on sapphire substrates using various mask materials. Studies of the LEO process via transmission electron microscopy (TEM) revealed that a major factor for the defect reduction in the laterally overgrown regions is the change of the dominant growth direction - from vertical in the window regions to lateral in the regions over the mask. Further, the development of the side facets morphology as a function of the growth time and temperature led us to the hypothesis that lateral growth should occur even without a mask or any supporting material. The new approach, pendeo-epitaxy is maskless lateral epitaxy where the selectivity is provided by the etched shape of the underlying seed GaN layer. Thus, when the underlying GaN is etched in elongated columns/trenches, with orientation similar to that of the stripes in the mask at the conventional LEO process, the side walls of the columns provide the crystallographic template for the lateral PE growth of free-standing GaN material. The examination of the morphology of the top surfaces, side facets, and interfaces of the LEO- and PE-GaN stripes with the underlying and adjacent interfaces, reveals their remarkable similarity with the thermally generated stress/strain gradient profiles as calculated via finite element analysis.The mechanisms of defect reduction in LEO and PE are similar, although through different process routes, and are related with the change of the dominant growth direction (from vertical to lateral), and the free-standing (PE) or quasi free-standing (LEO) growth of GaN, and the associated stress reduction. The mechanism for defect reduction in the SPER process is governed by the associated annealing phenomena and therefore is related to dislocation and grain boundary mobility and migration. Studies with TEM reveal that the as-grown aluminum nitride films on sapphire and silicon carbide substrates contain high density of defects, mainly threading dislocations in the order of 109 - 1012 cm-2, and low angle grain boundaries, as well. After the annealing of the heterostructures at 1600°C the structural defects in the AlN films are localized in the vicinity of the AlN/sapphire and AlN/6H-SiC interfaces, and are mostly stacking faults and dislocation lines parallel to the interface line. TEM and x-ray diffraction studies reveal the overall reduction of the dislocation density in the annealed AlN films with two-to-three orders of magnitude. The improved crystallographic quality of the annealed AlN films is discussed in terms of lattice and thermal mismatch strain relaxation.

2:00 PM G5.2
CAN LATERALLY OVERGROWN GaN LAYERS BE FREE OF STRUCTURAL DEFECTS? Zuzanna Liliental-Weber, Lawrence Berkeley National Laboratory, Berkeley, CA; D. Cherns, H.H. Wills Physics Laboratory, Bristol University, Bristol, UNITED KINGDOM.

Laterally overgrown GaN layers are known to have lower defect density than layers grown in the two step mode, leading to lasing in such material. However, x-ray diffraction from overgrown layers shows 'wings' in addition to the main peak. To understand these additional peaks, transmission electron microscopy was applied to plan-view and cross-section lateral-overgrown samples. The GaN, 3 μm thick, was grown on Al_2O_3, followed by 1.5 μm of SiO_2 stripes parallel to $[1\bar{1}00]$, with 4.5 μm windows. These layers were overgrown by a 7 μm thick GaN layer. Studies in cross-section show much higher defect density at both homoepitaxial/laterally (H/L) overgrown and at meeting fronts (MF) of laterally overgrown regions. The central parts of the overgrown areas had distinctly lower density of defects than those observed in the homoepitaxial parts. This was also confirmed by the study of plan-view samples which show formation of half-loops at each interface propagating mainly along the stripe direction. These half-loops are of a-type and mixed character with a large screw component, mainly originating at H/L interfaces and with threading parts. Where two laterally overgrown layers coalesce, some half loops are also formed. The threading parts are fixed at the interfaces and in-plane parts propagate and occasionally reach the opposite interface, or interact with each other. Some of the threading dislocations present at the edges of the homoepitaxial regions bend to form in-plane segments in the overgrown region. We believe dislocation half-loops are formed in order to accommodate tilt/twist at both interfaces. This tilt/twist leading to the additional peaks in x-ray diffraction was determined using large angle convergent-beam electron diffraction and is believed due to the difference in thermal expansion coefficients of GaN and SiO_2 and the strain along the stripe. The role of particular defects will be discussed at the meeting.

2:15 PM G5.3
REDUCTION OF DISLOCATION DENSITY IN GaN VIA FACET CONTROLLED ELO (FACELO) BY LP-MOVPE. H. Miyake, H. Mizutani, M. Narukawa, A. Motogaito, K. Hiramatsu, Dept of Electrical and Electronic Engineering, Mie Univ, Tsu, JAPAN; Y. Iyechika, T. Maeda, Tsukuba Research Laboratory, Sumitomo Chemical Co., Ltd, Tsukuba, JAPAN.

Epitaxial lateral overgrowth (ELO) with selective area growth is a promising technique to obtain high-quality GaN films. It was found that the two-step ELO with facet control is a useful technique to improve crystalline quality of the GaN films. Hereafter, we call this technique FACELO (Facet (Controlled (ELO). In this paper, we reported the FACELO GaN with threading dislocation (TD) density on the order of 10^6 cm^{-2}. The ELO of GaN by an LP-MOVPE system was performed on a 4.0 μm thick (0001) GaN with SiO_2 stripe masks along the $<1\bar{1}00>$ direction. For the facet control in ELO process, the growth temperature and the reactor pressure were varied from 950 to 1070°C and from 80 to 500 Torr, respectively. When the first step of ELO has vertical facets of $\{11\bar{2}0\}$, the SiO_2 masks are buried by further lateral growth. In this FACELO, the TDs penetrate the ELO layer and come up to the surface, so they exist only on the window area. On the other hand, when the first step of ELO has inclined facets of $\{11\bar{2}2\}$, the lateral growth rate is increased in the second step of ELO. In this case, the TDs bend towards $<11\bar{2}0>$ direction when the growth fronts meet the inclined $\{11\bar{2}2\}$ facets. In this way, the TD density on the window area is remarkably reduced

and that on total area is less than 2×10^7 cm^{-2}. In order to reduce the dislocation density further, the double FACELO is demonstrated. The first FACELO with stripe SiO_2 masks along $< 1\bar{1}00 >$ direction was performed by the 2-step process of the latter FACELO, and then the second FACELO with stripe masks along $< 10\bar{1}0 >$ direction was also performed by the same growth process. The TD is dramatically decreased and the density is 2-10 $\times$ 10^6 cm^{-2}.

2:30 PM G5.4
MAPPING OPTICAL AND ELECTRONIC VARIATIONS IN LATERAL EPITAXIAL OVERGROWN GaN FILMS.
Julia W.P. Hsu, M.J. Matthews, D.V. Lang, S. Richter, D. Abusch-Magder, R.N. Kleiman and A.M. Sergent, Bell Labs, Lucent Technologies, Murray Hill, NJ; Shulin Gu and T.F. Kuech, Department of Chemical Engineering, University of Wisconsin, Madison, WI.

While the dislocation density is significantly reduced in the LEO structures, the electrical and optical properties of this type of GaN films have not been fully investigated. Spatially resolved techniques are needed because different regions could contain different defects, impurities, and/or strain. Scanning probe microscopy (SPM) results on cross sectional LEO structures reveal five characteristically different regions: the GaN seed layer, the nucleation regions, the "wings" immediately above the SiO_x masks, the coalescent regions where two neighboring wings meet, and the bulk film. It is interesting to note that the wing regions show the same behavior in all three types of SPM as the HVPE interfacial region: leaky in reverse bias, smaller SCM signal, and EF lower in the gap. Confocal Raman spectroscopy and imaging confirm a high density of carriers (10^{19} to 10^{20} cm^{-3}) in the wings. The coalescence regions have a lower carrier density, $\approx 10^{19}$ cm^{-3}. The bulk film appears much lower doped, with a strong LO phonon peak and no hint of a plasmon peak in the Raman spectra. Since the wings are on top of the SiO_x masks, it is likely that O concentration is high in these regions, similar to the interfacial region. We also find that the physical properties are sensitive to specific growth conditions that are employed in these structures. This most likely arises from differences in point defects and/or incorporation of impurities.

2:45 PM G5.5
MEASUREMENT, CONTROL, AND MINIMIZATION OF WING TILT IN LATERALLY OVERGROWN GaN.
P.T. Fini[a], L. Zhao[a], G.B. Stephenson[b], A. Munkholm[c], Carol Thompson[b,d], J.A. Eastman[b], M.V. Ramana Murty[b], S.P. DenBaars[a], J.S. Speck[a]; [a]Materials Dept., Univ. of California - Santa Barbara, Santa Barbara, CA; [b]Materials Science Div., Argonne National Laboratory, Argonne, IL; [c]Chemistry Div., Argonne National Laboratory, Argonne, IL; [d]Dept. of Physics, Northern Illinois Univ., Dekalb, IL.

Despite recent advances in GaN-based device performance enabled by lateral epitaxial overgrowth (LEO), some difficulties remain in controlling the structural quality of the overgrown material, particularly for fully coalesced films. Often the crystal planes in the 'wings' (overgrown GaN) exhibit tilts away from those in the 'window' (seed) stripe regions. Coalescence of wings from neighboring stripes may then generate additional extended defects. Although the exact origins of wing tilt are unknown at the current time, it is obviously desirable to minimize or eliminate wing tilt altogether. In this presentation, we discuss the use of x-ray diffraction in conjunction with scanning electron microscope (SEM) measurements to determine the dependence of wing tilt on stripe morphology. We empircally correlate wing tilt with the ratio of wing width (w) to height (h) as measured in cross section, which is directly dependent on growth conditions and 'fill factor' (the ratio of open width to pattern period. Wing tilt values lower than 0.1° have been achieved by controlling the stripe cross-sectional aspect ratio. We have also recently performed successful *in situ*, real-time x-ray diffraction measurements of wing tilt **during** lateral overgrowth in a vertical two-flow MOCVD chamber mounted on a 'z-axis' surface diffractometer at the Advanced Photon Source. During LEO, wing tilt emerged early (< 300s) in the growth and rapidly reached a value of ~1°, with an increase to ~1.19° after 3600s of growth. Upon cooldown to room temperature, tilt increased slightly to ~1.36°, indicating that thermally-induced stresses at the wing-mask interface are not dominant in determining tilt magnitude. These results as well as complementary SEM and TEM measurements will be discussed, with an emphasis on controlling LEO wing tilt via an understanding of its origins during growth.

3:30 PM *G5.6
CHARACTERISTICS OF FIELO-GaN GROWN BY HYDRIDE VAPOR PAHSE EPITAXY.
Akira Usui, Haruo Sunakawa, Kenji Kobayashi, Heji Watanabe, Atsushi A. Yamaguchi, Masashi Mizuta, System Devices and Fundamental Research, Photonics and Wireless Device Research Labs., NEC Corporation, Tsukuba, Ibaraki, JAPAN.

We have reported the HVPE growth of thick GaN layers by a facet-initiated epitaxial lateral overgrowth(FIELO) method with low dislocation density of 10^{6-7} cm^{-2}. The FIELO-GaN substrate was successfully applied to the fabrication of InGaN MQW blue laser diodes (LD). In this paper, characteristics of FIELO-GaN, in particular, that in the vicinity of the surface, is reported, which are obtained from crystallographic and optical studies of FIELO-GaN. We have reported that the unique dislocation behavior of FIELO GaN causes the tilting of c-axis in the overgrown regions. By using scanning reflection electron microscopy (SREM), the dependence of the tilt angle on the thickness of FIELO-GaN was investigated. SREM images were obtained by recording the change of specular reflection spot intensity. On a 50-μm-thick FIELO-GaN, the clear stripe contrast reflecting the tilt on the mask region was observed, while the contrast was found to almost disappeared on a 100-μm-thick FIELO-GaN. This indicates that the tilt angle of overgrowth regions was recovered to less than 0.05° in the thick sample. The crystal quality of FIELO-GaN was evaluated by x-ray rocking curve measurements. (0002) and $(10\bar{1}0)$ diffraction peaks were used. We indicate that the FWHM of these peaks should be reduced with the decrease of the dislocation density. The FWHM of (0002) diffraction peaks and $(10\bar{1}0)$ diffraction peaks for samples having the dislocation density of the order of 10^6 cm^{-2} was 90-130 arcsec and 130-180 arcsec, respectively. Finally, the optical quality of FIELO-GaN was evaluated by photoluminescence (PL) decay time. The decay time for FIELO-GaN was much longer than those for conventional MOVPE-grown GaN and the longest decay time was 1.3 ns. These results indicate that the use of FIELO-GaN substrate is promising for the fabrication of high-performance LDs.

4:00 PM G5.7
HETEROEPITAXY AND CHARACTERIZATION OF LOW-DISLOCATION-DENSITY GaN SINGLE CRYSTAL ON PERIODICALLY GROOVED SUBSTRATES.
T. Detchprohm, M. Yano, R. Nakamura, S. Sano, S. Mochiduki, H. Amano, I. Akasaki, High-Tech Research Center, Meijo University; Dept of Electrical & Electronic Engineering, Meijo University; Dept of Materials Science and Engineering, Meijo University.

Growing GaN and related nitride single crystal films on sapphire substrates using low-temperature (LT) buffer layer technique [1] has been significantly contributed to developing optoelectronic and microelectronic devices. However, to further improve the device performance, there is necessity to reduce dislocation density formed inside the materials. There are several efforts based upon the above technique to gain low-dislocation-density materials such as lateral epitaxial overgrowth [2], LT interlayer introduction [3], and mass transport techniques [4]. Demonstrations of characteristics improvement were made for devices using low-dislocation-density GaN and related materials [5,6]. Here, we propose a newly developed heteroepitaxial technique using a periodically grooved substrate to achieve a low-dislocation-density GaN single crystal film. Periodically grooved substrates of c-plane sapphire, Si(111) and 6H-SiC (0001) were used for heteroepitaxy of GaN single crystal in metal organic vapor phase epitaxy (MOVPE) method. Width of a single groove was approximately 5 μm in a 10 μm interval. Since this technique does not require GaN single crystal seeds and/or layers prior to a growth, a substrate can be thoroughly cleaned up and, hence, less process contaminations can be provided. Prior to the GaN growth, a LT-AlN buffer layer was deposited on a sapphire substrate, while a thin AlGaN single crystal film was deposited on a 6H-SiC or Si substrate. By controlling facet formation, we were able to prepare low-dislocation-density GaN verified via TEM. GaN films grown on these substrates showed periodic change in both PL peak intensities and peak wavelengths. Increasing in peak intensities was observed for GaN with low dislocation density whereas peak wavelength distribution correlated to stress distribution. Details of growth mechanism and film properties will be discussed. This work was supported in part by the Japan Society for the Promotion of Science Research for the Future Program in the Area of Atomic Scale Surface and Interface Dynamics under the project of "Dynamic Process and Control of the Buffer Layer at the Interface in a Highly-Mismatched System (JSPS96P00204)", and the Ministry of Education, Science, Sports and Culture of Japan, (contract numbers 11450131, 12450017 and 12875006). [1] H. Amano, N. Sawaki, I. Akasaki, and Y. Toyoda, Appl. Phys. Lett. 48,353 (1986). [2] A. Usui, H. Sunakawa, A. Sakai, and A.A. Yamaguchi, Japan. J. Appl. Phys 36 (7B), L899 (1997). [3] M. Iwaya, T. Takeuchi, S. Yamaguchi, C. Wetzel, H. Amano, and I. Akasaki, Japan. J. Appl. Phys. 37, L316 (1998). [4] S. Nitta, T. Kashima, M. Kariya, Y. Yakawa, S. Yamaguchi, H. Amano, and I. Akasaki, Mat. Res. Soc. Symp. Proc. 595, W2.8.1 (2000). [5] P. Kozodoy, J.P. Ibbeston, H. Marchand, P.T. Fini, S. Keller, S.P. DenBaars, J.S. Speck, and U.K. Mishra, Appl. Phys. Lett. 73, 976-977 (1998). [6] C. Pernot, A. Hirano, M. Iwaya, T. Detchprohm, H. Amano, and I. Akasaki, Japan. J. Appl. Phys. 38, L487 (1999).

4:15 PM G5.8
DIFFERENCES IN STRESS RELEASE BETWEEN MBE AND

MOVPE GROWN AlGaN SINGLE LAYERS AND SUPER-LATTICES. S. Einfeldt, M. Diesselberg, T. Böttcher, H. Heinke, D. Hommel, Institute of Solid State Physics, University of Bremen, GERMANY.

Release of tensile plane stress in AlGaN single layers and AlGaN/GaN short period superlattices grown on thick GaN buffer layers is investigated with particular focus on the impact of the deposition technique. Therefore films of different composition and thickness have been grown by molecular beam epitaxy (MBE) and metalorganic vapor phase epitaxy (MOVPE). Relaxation is found to start via crack channeling when a certain critical strain energy per unit film area is exceeded. The onset of cracking and the connected extent of stress release is different between films grown by MBE and MOVPE. The critical strain energy for MBE structures is about twice as large as that for MOVPE structures indicating different fracture toughnesses. While the behaviour of MOVPE layers roughly fits to Griffiths concept of balancing the released strain energy and the introduced surface energy per crack, an additional activation barrier is postulated for crack formation in MBE layers. Moreover, the stress released per crack is often higher for MOVPE than for MBE films and mostly higher than expected from theoretical stress distributions in cracked films. In explanation of this, misfit dislocations are proposed to nucleate at crack channels and glide at AlGaN/GaN interfaces [1]. Differences in interface roughness, growth temperature and dislocation density are exploited to discuss different relaxation efficiencies of cracks in MBE and MOVPE films. [1] S.J. Hearne et al., Appl. Phys. Lett. 76, 1534 (2000).

4:30 PM G5.9
OPTICAL PROPERTIES OF MBE GROWN CUBIC AlGaN EPILAYERS AND AlGaN/GaN QUANTUM WELL STRUCTURES. D.J. As, T. Frey, D. Schikora, and K. Lischka, Universität Paderborn, FB-6 Physik, Paderbon, GERMANY; R. Goldhahn, S. Shokhovets, TU Ilmenau, Institut für Physik, Ilmenau, GERMANY.

For advanced optoelectronic devices, like light emitting diodes (LEDs) or laser diodes (LDs) Al containing cladding layers or barriers are necessary. The commonly used hexagonal $Al_yGa_{1-y}N$/GaN heterostructures show an inherently strong spontaneous polarisation oriented along the hexagonal c-axis as well as strain induced piezoelectric polarisation. Such polarization induced electric fields in strained quantum wells can cause the spatial separation of electrons and holes resulting in a severe reduction of optical recombination efficiency. Using the metastable cubic modifications of $Al_yGa_{1-y}N$ and GaN such piezoelectric effects can be avoided if the samples are grown in (001) direction. In this contribution we report on the optical properties of cubic $Al_yGa_{1-y}N$ /GaN heterostructures on GaAs (001) substrates grown by radio-frequency plasma-assisted molecular beam epitaxy (MBE). Spectroscopic ellipsometry (SE) and cathodo-luminescence (CL) are used to characterize the optical properties of the $Al_yGa_{1-y}N$ epilayers. The Al content y of the alloy is independently determined by high resolution x-ray diffraction (HRXRD) and Rutherford backscattering (RBS) and is varied between $0.07 < y < 0.20$. X-ray diffraction reciprocal space maps demonstrate the good crystal quality of the cubic $Al_yGa_{1-y}N$ films. Both SE as well as room temperature CL of the $Al_yGa_{1-y}N$ epilayer show a linear increase of the band gap with increasing Al-content similar to the observations made on cubic $Al_yGa_{1-y}N$ epilayers grown on thick 3C-SiC substrates. For y = 0.09 room temperature CL is dominated by near-band-edge emission with a linewidth of about 150meV. In addition, a pseudomorphically strained cubic 10 x (2.5nm GaN/ 5nm $Al_{0.10}Ga_{0.90}N$) multi-quantum well (MQW) structure has been realized. Room temperature and low temperature cathodoluminescence clearly demonstrates strong radiative recombination due to quantized states in the GaN well layer at a photon energy of 3.3 eV.

4:45 PM G5.10
GROWTH AND STRUCTURE OF GaN/C-PLANE SAPPHIRE WITH A NEW EPITAXIAL RELATIONSHIP. E.V. Etzkorn, P.R. Tavernier, D.R. Clarke, Materials Department, University of California, Santa Barbara, CA.

The standard growth of GaN on c-plane sapphire results in an epitaxial relationship of $(0001)_{GaN} \parallel (0001)_{sapphire}$, $[11\bar{2}0]_{GaN} \parallel [10\bar{1}0]_{sapphire}$, in which the anion sub-lattice is continuous across the interface. Under appropriate low-temperature nucleation conditions in HVPE growth, however, we have been able to produce 2" diameter films having an alternate epitaxial relationship of $(0001)_{GaN} \parallel (0001)_{sapphire}$, $[11\bar{2}0]_{GaN} \parallel [\bar{1}3\bar{2}0]_{sapphire}$ and $[11\bar{2}0]_{GaN} \parallel [12\bar{3}0]_{sapphire}$. This relationship corresponds to a rotation from the standard orientation of $\pm$ 19.1° around the c-axis. These rotated GaN films are of similar structural and morphological quality to standard films, with a typical omega rocking-curve FWHM of approximately 325 arcsec as measured both on- and off-axis. Room-temperature Raman piezospectroscopy indicates that the rotated films are under significantly less tensile stress during growth than corresponding unrotated films. In addition, these films are usually crack-free or nearly crack-free. The initiation and structural development of films with this alternate epitaxy are examined, and an explanation in terms of a coincident site lattice model and a competition between positively-rotated and negatively-rotated regions is proposed. The energetics of GaN nucleation and growth, and the sensitivity to reactor conditions, including impurities, are discussed in light of these results.

SESSION G6: POSTER SESSION
OPTICAL PROPERTIES AND LIGHT EMITTERS
Tuesday Evening, November 28, 2000
8:00 PM
Exhibition Hall D (Hynes)

G6.1
DEFECT RELATED OPTICAL PROPERTIES OF UNDOPED N-TYPE GaN. S.J. Chung[1], O.H. Cha[1], Y.S. Kim[1], C.-H. Hong[1], H.J. Lee[1], M.S. Jeong[1,2], J.O. White[2] and E.-K. Suh[1,2]. [1]Semiconductor Physics Research Center and Department of Semiconductor Science and Technology, Chonbuk National University, Chonju, KOREA; [2]Frederick Seitz Materials Research Laboratory, University of Illinois at Urbana-Champaign, Urbana, IL.

Deep level defect related optical properties of undoped n-type GaN grown by metal organic chemical vapor deposition are investigated using photoluminescence(PL), photoconductivity(PC), and persistent photoconductivity(PPC) measurements. PL, PC, and PPC results manifest a strong correlation in properties related to deep levels. Samples which emit the YL exhibit a broad PC peak at 1.9 eV due to the photoionization of deep levels as well as the persistent photoconductivity effect, whereas samples with no YL have no PC peak in the forbidden gap and no PPC at any photon energy, suggesting that they have a common origin of deep level defects. Furthermore, two types of PPC behavior were observed depending on the sample thickness: typical stretched exponential decay in relatively thick samples, and photocurrent quenching and negative photocurrent followed by a reduction of the dark current in thin samples. From the temporal behavior of the PC, the anormalous PPC phenomenon are attributed to the photoinduced metastable electron traps in a highly defective layer formed near the GaN/sapphire interface due to large lattice and thermal mismatch. These traps seem to disappear slowly after the illuminating light is turned off. The defective interface layer is formed some period after growth as the strain relaxation undergoes in the sample.

G6.2
LUMINESCENCE OF As-DOPED GaN BY MBE UNDER As^2 AND As^4. Andrew J. Winser, Ian Harrison, University of Nottingham, School of Electrical and Electronic Engineering, Nottingham, UNITED KINGDOM; Carl S. Davis, Sergei V. Novikov, Tin S. Cheng, Richard P. Campion, C.Thomas Foxon, University of Nottingham, School of Physics and Astronomy, Nottingham, UNITED KINGDOM.

The strong blue emission from As doped GaN may provide an alternative to InGaN/GaN LED's. In this paper we shall report on the room and low temperature photoluminescence from As doped GaN grown by plasma-assisted molecular beam epitaxy under a various As^2 and As^4 fluxes. The As has several effects on the luminescence properties of GaN. The intensity of the wurzite band edge reduces, there is an increase in the cubic band edge luminescence and a finally strong deep blue emission occurs. The deep luminescence consists of three overlapping bands at approximately 2.46eV, 2.68eV and 2.89eV. The positions of these peaks depend on the As flux. (These are not caused by interference fringes.) The variation of the intensity of cubic and the blue emission have different dependencies with As flux. For the case of the blue emission the power dependency (Flux) $^{\gamma}$, this is 0.74 and 0.49 for As^2 and As^4 respectively. The cubic case has power dependencies of 0.53 and 0.37 for growth under As^2 and As^4. From thermodynamic arguments the As surface concentration will have a power dependence on the flux. For As^2 this will be 0.5 and 0.25 for As^4. Therefore, these results provide evidence for the involvement of cubic GaAs in the formation of GaN.

G6.3
EFFECT OF THERMAL ANNEALING ON THE PHOTO-LUMINESCENCE PROPERTIES OF A GaInNAs/GaAs SINGLE QUANTUM WELL. L. Grenouillet, C. Bru-Chevallier, G. Guillot, Institut National des Sciences Appliquées, Laboratoire de Physique de la Matiére, Villeurbanne, FRANCE; P. Gilet, P. Ballet, P. Duvaut, A. Million, A. Chenevas-Paule, LETI/CEA-G-DOPT, Grenoble, FRANCE.

The GaInNAs semiconductor alloy is being intensively studied for

both its fundamental properties and its potential for 1.3 μm optoelectronic device applications. However, the N incorporation in GaInAs generally induces a degradation of the photoluminescence (PL) properties. A rapid thermal annealing (RTA) is usually carried out on the samples to improve the PL efficiencies, even though the mechanisms induced by RTA are not yet well understood. In this report, the effect of RTA on the PL properties is studied in detail. Two samples were grown by gas source molecular beam epitaxy on semi-insulating 3 in. GaAs (100) substrates: a 7 nm $Ga_{0.75}In_{0.35}N_{0.02}As_{0.98}$/GaAs single quantum well (SQW) and a 7 nm $Ga_{0.75}In_{0.35}As$/GaAs SQW as a reference sample. Photoluminescence and photoreflectance measurements as a function of temperature were performed on both samples to determine the energy of the radiative recombinations and that of the confined levels. In the N-containing sample, it is shown that the PL emission at low temperatures comes preferentially from localized states located below the E_1H_1 energy. This phenomenon induces an inverted S-shape dependence of the PL peak energy with temperature. The study of the RTA effect on the PL properties shows that i) the strong localization effects induced by nitrogen decrease with increasing RTA time, ii) the RTA-induced blue shift of the PL peak cannot only be attributed to the In-Ga interdiffusion, iii) the full width at half maximum of the PL peak decreases and the PL intensity increases with increasing RTA time. This work was supported by a BRITE EuRam program, Contract No. BRPR-CT98-0721, Project No. BE97-4947.

G6.4
COMPARATIVE STUDY OF HVPE- AND MOCVD-GROWN LASING STRUCTURES FOR UV APPLICATIONS. Sergiy Bidnyk, J.B. Lam, A. Elgawadi, G.H. Park, J. Krasinski, J.J. Song, Center for Laser and Photonics Research and the Dept of Physics, Oklahoma State University, Stillwater, OK; D.V. Tsvetkov and V.A. Dmitriev, Technologies and Devices International, Inc., Gaithersburg, MD.

We performed a comparative study of the optical properties of highly excited (Al)GaN epilayers and heterostructures grown by two different techniques: hydride vapor phase epitaxy (HVPE) and metalorganic chemical vapor deposition (MOCVD). We successfully achieved efficient low-threshold stimulated emission (SE) in HVPE-grown GaN epilayers and GaN/AlGaN heterostructures both at 10 K and room temperature. We found that the SE threshold and efficiency of the HVPE-grown samples at 10 K approaches that of high-quality MOCVD-grown structures. Through the temperature-dependent studies, we demonstrate that the photoluminescence efficiency of the HVPE-grown samples decreases more rapidly through the temperature range of 10 K to 300 K. We attribute this phenomenon to a higher density of non-radiative recombination channels in HVPE-grown structures in comparison to MOCVD-grown structures. The effects of AlGaN confinement layers on the emission energy of the GaN-active-region structures have been thoroughly investigated. To our knowledge, this study represents the first demonstration of SE in HVPE-grown (Al)GaN heterostructures.

G6.5
WHITE LIGHT EMISSION FROM ELECTROLUMINESCENT DEVICES USING AN AMORPHOUS AlN: MIXED DOPANT THIN-FILM PHOSPHOR. A.L. Martin, M.L. Caldwell, M.E. Kordesch, H.H. Richardson, C.M. Spalding, P.G. Van Patten, Condensed Matter & Surface Science Program, Ohio University, Clippinger Laboratories, Athens, OH.

AlN: Cu, Mn, Tb films, ~200 nm thick, were grown on p-doped silicon (111) substrates using RF magnetron sputtering in a nitrogen atmosphere. SIMS, IR reflective microscopy, XRD, XRF, and SEM imaging were used for film characterization. After film activation by annealing in a nitrogen atmosphere, cathodoluminescence (CL) and photoluminescence (PL) studies were performed at low and room temperatures. Tangent studies with singularly doped AlN thin-films indicate that the emission spectra from Cu emitted blue at ~475 nm, Mn emitted red at ~680 nm and ~700 nm, and Tb emitted green at ~500 nm and ~550 nm. The emission spectrum from a Cu, Tb, Mn doped AlN thin-film revealed a broad peak centered at ~530 nm. The relative amount of the blue, green and red emitters were adjusted to yield the best white light emitter. An alternating-current thin-film electroluminescent (ACTFEL) device was formed by growing the white emitting phosphor on top of p-doped Si (111), the bottom electrode, and capping the device with indium tin oxide (ITO) dots used as the top electrode.

G6.6
STUDIES OF ELECTROLUMINSCENT DEVICES FROM AMORPHOUS AlN:Mn, Cu, and Cr FILMS. Meghan L. Caldwell, A.L. Martin, C.M. Spalding, M.E. Kordesch, H.H. Richardson, P.G. VanPatten, Ohio Univ, Dept of Chemistry and Biochemistry, Athens, OH.

Many efforts have been and still are underway to produce an efficient device that has visible color emission from a rare-earth doped semiconductor. Rare-earth atoms are chosen because their atomic transitions are not significantly affected by the host material. Wide band gap III-V semiconductors are known to have many advantages over other II-VI or smaller band gap semiconductors because of their superior electro-optical, thermal and chemical properties as well as emission into the deeper blue and ultra-violet. Most of the work in this area has been concentrated on crystalline and polycrystalline GaN but recently visible emission has been reported from amorphous III nitride materials doped with Er3, Pr3, Tm3 and Tb3. AlN has a wider band gap than GaN and an Er doped amorphous AlN phosphor material has been used in an alternating current thin film electroluminscent device. We have also reported visible luminescence from Mn polycrystalline AlN and recently have observed visible luminescence from Mn doped amorphous AlN. The luminescence has a peak maximum at 690 nm compared to 600 nm in crystalline AlN. We have extended these results to other transition metal dopants: Cu and Cr. Copper gives extremely strong broad band luminescence peaked in the blue at 475 nm. The peak position shifts into the green (530 nm) when co-doped with Mn and Tb. The lower luminescence yield of Mn4 relative to Tb3 is believed to be from charge compensation problems associated with Mn ions having an even charge (Mn2 or Mn4) compared to the 3 charge of the III nitride semiconductor. Cr and other 3 transition metal ions will be investigated because these ions should not suffer from the charge compensation problems observed with Mn.

G6.7
PHOTOLUMINESCENCE STUDY OF DEFECTS IN GaN GROWN BY MOLECULAR BEAM EPITAXY. M.A. Reshchikov, M.H. Zhang, J. Cui, F. Yun, and H. Morkoc, Virginia Commonwealth University, Richmond, VA; P. Visconti, Virginia Commonwealth University, Richmond, VA and Istituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY.

Comprehensive photoluminescence (PL) experiments have been performed on a set of GaN epitaxial layers grown under different conditions by molecular beam epitaxy method utilizing both RF source and ammonia for active nitrogen. In many samples grown with RF plasma as the nitrogen source, we have observed two new PL bands with maximum at about 1.8 eV (red band) and 2.4 eV (green band) and full width at half maximum of about 0.25 eV. These bands have been attributed to deep acceptors, which are presumably native point defects. Both PL bands are thermally quenched at temperatures above 100 K with activation energy less than 150 meV and totally disappear at room temperature. Two models of this quenching will be discussed. It is tentatively concluded that the recombination via these acceptors may be partially nonradiative and these defects could be effective killers of optical recombination in GaN. The temperature induced variations in shape and position of the red and green PL bands are explained in the configuration coordinate model for defects with strong electron-phonon coupling. The energy of the local phonon mode and the Huang-Rhys factor are estimated for the defect responsible for the green band. We have also studied the effect of excitation intensity and temperature on sharp PL peaks observed in some GaN samples at photon energies in the range 3.0-3.43 eV. These peaks are tentatively attributed to excitons bound to structural defects. By employing the selective wet etching in these samples, we attempted to identify the structural defects responsible for the sharp PL peaks in GaN. The effect of the selective and nonselective etching on the red and green bands has also been studied.

G6.8
OPTICAL PROPERTIES OF InAlGaN QUATERNARY ALLOYS. J. Li, K.B. Nam, K. Kim, J.Y. Lin, and H.X. Jiang, Department of Physics, Kansas State University, Manhattan, KS.

InxAlyGa1-xN quaternary alloys of different In- and Al-contents have been grown on sapphire substrates with GaN buffer layers (25 nm) by low pressure MOCVD. Structural and surface properties and chemical compositions were characterized by various techniques, including X-ray diffraction (XRD), Rutherford back scattering (RBS), secondary ion mass spectroscopy (SIMS), energy dispersive system (EDS), scanning electron microscopy (SEM) and atomic force microscopy (AFM) measurements. The growth condition dependence (temperature, pressure, metalorganic sources and carrier gases follow rates, etc.) of growth rate, surface morphology, electrical properties (carrier concentration and mobility) and optical properties (PL emission peak positions, emission linewidth, and emission intensities) were investigated systematically. Time-resolved PL (TRPL) has been used to study the optical transitions and quantum efficiencies of these InxAlyGa1-xN quaternary alloys. It was found from XRD, RBS, and TRPL results that InxAlyGa1-xN quaternary alloys that are lattice-matched to GaN (y = 4.7 x) have the highest electrical and optical qualities. The optical recombination processes in these InxAlyGa1-x-yN quaternary alloys have been measured at different temperatures and excitation light intensities. Comparison

measurements on the emission efficiency, linewidth, and recombination lifetime have been carried out for the InxAlyGa1-x-yN quaternary alloys, InGaN and AlGaN ternary alloys, and GaN epilayers. We found that the optimal growth conditions as well as the electrical and optical properties of the InxAlyGa1-x-yN quaternary alloys are more closely correlated with those of the InGaN alloy system than the AlGaN alloy system. Heterostructures and quantum wells of GaN/InxAlyGa1-x-yN and InxAlyGa1-x-yN/ Inx'Aly'Ga1-x'-y'N have also been fabricated and studied. Potential applications of the lattice-matched GaN/InxAlyGa1-x-yN and InxAlyGa1-x-yN/ Inx'Aly'Ga1-x'-y'N heterostructure and QWs for blue/UV light emitting diodes (LEDs), laser diodes (LDs), solar-blind UV detectors, and heterojunction field-effect transistors (FETs) have also been explored.

G6.9
ENHANCED LIGHT EMISSION FROM InGaN/GaN QUANTUM WELL BLUE AND GREEN INTER-CONNECTED MICRO-LEDs. J.Y. Lin, S.X. Jin, J. Li, and H.X. Jiang, Department of Physics, Kansas State University, Manhattan, KS.

Interconnected blue and green micro-LEDs have been fabricated from InGaN/GaN single quantum wells (SQWs) grown by low pressure MOCVD. An array comprising a plurality of these micro-LEDs, which are interconnected in a manner that they are turn on and off simultaneously, fits into the same area taken up by a conventional broad-area LED. Each micro-LED is approximately 5-20 micrometers. The performance characteristic of these interconnected micro-LEDs, including I-V and L-I characteristics, turn-on and turn-off speeds, emission wavelength and linewidth, have been measured and compared with those of the conventional broad-area LEDs. The output power of our conventional broad-area blue LEDs (300 micron x 300 microns) was around 1.0 mW (450 nm) at 20 mA and VF was around 3.8 V. For interconnected micro-LEDs, while VF was almost unchanged, the total light output power was increased by as much as 35%. The effects of size of micro-LEDs as well as the spacing between the micro-LEDs have been investigated systematically. We found three advantages by replacing a conventional broad-area LED with a plurality of inter-connected micro-LEDs. First, the light emission is enhanced in micro-LEDs over the conventional broad-area LEDs due to the micro-cavity effect[1]. Second, lattice-mismatch induced strain in InGaN/GaN SQWs is relieved or partially relieved in micro-size LEDs due to the reduction of the lateral size of each micro-LED, which enhances the radiative recombination rate of injected carriers and hence the light emission efficiency. Third, by replacing a conventional broad-area LED with many of these inter-connected micro-LEDs, the light extraction efficiency and hence the external quantum efficiency are significantly enhanced. Finally, the fabrication processes of these interconnected micro-LEDs are almost the same as those of the conventional broad-area LEDs, which suggests that the total yield for these novel micro-LEDs is expected to be the same as the conventional broad-area LEDs. 1. "GaN microdisk light emitting diodes", S.X. Jin, J. Li, J.Z. Li, J.Y. Lin, and H.X. Jiang, Appl. Phys. Lett. 76, 631 (2000).

G6.10
RAMAN SPECTROSCOPY STUDIES IN InGaN/GaN WURTZITE EPITAXIAL FILMS. M.R. Correia[a], S. Pereira[a], N. Pinho[a], T. Monteiro[a], E. Pereira[a] and E. Alves[b]. [a]Departamento de Fisica, Universidade de Aveiro, PORTUGAL; [b]I.T.N., Departamento de Fisica, Sacavem, PORTUGAL.

Technological and fundamental interest in InGaN continues to rise, consequently it is increasingly important to establish the best techniques to assess relevant aspects of this material. Raman spectroscopy is a convenient non-destructive tool for the characterisation of semiconductors. As a rather sensitive, local, and fast technique it is a widely used method, namely in the study of optoelectronic properties of III-Nitrides heterostructures. The optimisation of this technique applied to InGaN demands the establishment of the strain and indium content dependence for the Raman active modes. For this purpose the knowledge of the phonon frequencies and respective symmetry of the related binary compounds, GaN and InN, is fundamental. Raman modes for GaN are well known, however the measurement of phonon modes for relaxed InN has only recently been reported [1]. In this work we study a set of nominally undoped epitaxial $In_xGa_{1-x}N$ wurtzite films grown on (0001) sapphire substrates. In order to separate the contribution of the strain and indium content in the phonon mode frequency, indium mole fraction was determined using a strain insensitive method, Rutherford backscattering spectroscopy (RBS). Strain was estimated by comparing the lattice constants measured by X-ray diffraction (XRD) with the relaxed lattice parameters given by Vegard's law. Samples with comparable indium content, but under different states of strain (relaxed and strained) were used as reference. This allowed an independent knowledge of the different Raman shift modes behaviour with strain and composition. We also assess the potentiality of Raman for the evaluation of crystalline quality (by the peak FHWM) comparing the results obtained with well-established methods such as XRD and RBS. Reference: [1] J.S. Dyck, K. Kim, S. Limpijumnong, W.R.L. Lambrecht, K. Kash, and J.C. Angus, Solid State Communications 114 (2000) 355-360.

G6.11
InGaN/GaN BLUE LIGHT EMITTERS ON Si. A. Dadgar, S. Richter, J. Bläsing, T. Riemann, A. Diez, P. Veit, J. Christen, and A. Krost, Otto-von Guericke Universität Magdeburg, Institut für Experimentelle Physik, Magdeburg, GERMANY; A. Alam and M. Heuken, AIXTRON AG, Aachen, GERMANY; A. Strittmatter and D. Bimberg, Technische Universität Berlin, Institut für Festkörperphysik, Berlin, GERMANY.

Blue and green GaN based LEDs are commercially available for several years now. Usually they are grown on sapphire or SiC substrates. Compared to Si these substrates have lower lattice and thermal mismatch to GaN but also lower heat conductivity, isolating behavior in the case of sapphire and much higher price especially in the case of SiC substrates. Therefore growth of GaN based devices on Si substrates offers the chance of reducing the cost of GaN based devices by lower growth cost and easier processing. First GaN based InGaN/GaN LEDs were already reported two years ago but only little has been published since then. We present a study of electrically pumped InGaN/GaN light emitters on Si. The samples were grown by MOCVD on (111) Si substrates with different buffer layers. The diodes show blue emission easily visible with the naked eye at daylight. We will discuss the influence of buffer and interlayers on the electrical, optical and structural properties of the luminescent devices.

G6.12
PHOTOLUMINESCENCE AND CATHODOLUMINESCENCE INVESTIGATIONS OF PIEZOELECTRIC QUANTUM WELLS. E.M. Goldys, Division of Information and Communication Sciences, Macquarie University, Sydney, AUSTRALIA; M. Godlewski, Institute of Physics, Polish Academy of Sciences, Warsaw, POLAND; M.R. Phillips, University of Technology, Sydney, AUSTRALIA; A.A. Toropov, Ioffe Institute, St. Petersburg, RUSSIA.

We have examined multiple quantum well (QW) AlGaN/GaN structures with strain-free QWs and strained AlGaN barriers, with several QWs of varying widths. In such structures strong electric fields due to the piezoelectric effect can be anticipated. The influence of these fields is reflected in the red shift of the observed QW emission peaks, as well as in the reduction of the oscillator strength of the transitions and their photoemission decay time. We report extremely long decay times, in the range of microseconds in the wide wells and compare the observed oscillator strengths and decay times with theoretical calculations. The cathodoluminescence measurements show the QW emission peaks as well as the yellow emission band (YL). The QW peaks are less red-shifted compared to their PL positions due to a higher excitation intensity. We have examined the in-plane uniformity of the QW and YL emissions and a pronounced granular texture was found. The spot-mode spectra identified that the most significant variations occur in the wider wells. The QW emissions also vary with beam current and the spectra taken in these conditions show changes consistent with the screening effects. The cathodo-luminescence spectra taken at increasing aceleration voltage provide an insight into depth-dependent properties of the examined structures. The spectra show an unexpectedly small contribution from the substrate emission. Theoretical estimates of the electron generation rate predict that the substrate emission should be clearly observed at higher voltages used. This apparent contradiction we explain by a strong influence of piezoelectric fields on the behaviour of primary and secondary electrons in the specimen. Such strong influence has not been reported earlier.

G6.13
IR-VUV DIELECTRIC FUNCTION OF $Al_{1-x}In_xN$ DETERMINED BY SPECTROSCOPIC ELLIPSOMETRY. A. Kasic[1,2], M. Schubert[1,2], B. Rheinländer[1], J. Off[3], F. Scholz[3], C.M. Herzinger[4]. [1]University of Leipzig, Dept. of Semiconductor Physics, Leipzig, GERMANY; [2]CMOMR, University of Nebraska, Lincoln, NE; [3]University of Stuttgart, 4th Physics Institute, Stuttgart, GERMANY; [4]J.A. Woollam Co., Inc., Lincoln, NE.

Spectroscopic Ellipsometry (SE) from the mid-infrared (IRSE; ~300 cm^{-1} ...) to the vacuum-ultraviolet (VUVSE; ... ~9 eV) spectral range is used to determine the optical properties of $Al_{1-x}In_xN$ thin films for indium contents $0.09 \leq x \leq 0.23$. $Al_{1-x}In_xN$ exhibits the largest band-gap variation of ternary group III nitride compounds and is a promising material for active layers in LEDs and LDs emitting in the UV to IR spectral region. To the best of our knowledge no results for the phonon modes or the near-band gap dielectric functions of $Al_{1-x}In_xN$ have been reported so far. We use VUVSE and IRSE as novel techniques to study non-destructively phonon and band-gap

properties in thin AlInN films. Approximately 0.1 ... 0.2 μm thick $Al_{1-x}In_xN$ films were grown on c-plane sapphire by MOCVD at 750°C. A thin α-AlN nucleation layer followed by a $\sim$0.5 μm thick high-quality α-GaN layer was deposited prior to the growth of some of the AlInN films. High-resolution x-ray diffraction was employed to determine the $Al_{1-x}In_xN$ film composition under assumption of Vegard/s law. The SE data were analyzed using an anisotropic parameterized dielectric function model for the AlInN films. We observe a one-mode behavior for the $Al_{1-x}In_xN$ E_1(TO) phonon mode. We find that the E_1(TO) lattice phonon frequency depends linearly on the $Al_{1-x}In_xN$ in-plane strain. From the strain induced shift of the E_1(TO) mode we estimate the deformation potential constants. We assume elastic constants C_{13} and C_{33} using a linear interpolation between the two binaries. The broadening of the E_1(TO) phonon mode indicates the crystalline quality of the $Al_{1-x}In_xN$ films. Compressive strained films (x > 0.17) and films grown directly on sapphire substrates show significantly poorer crystal quality. The IRSE data reveal that the free-electron concentration is below $1x10^{17}$ cm^{-3}. We further discuss fundamental band-gap and higher energy critical-point features.

G6.14
Abstract Withdrawn.

G6.15
INFLUENCE OF DEPTH PROFILES ON LUMINESCENCE PROPERTIES OF Er-DOPED GaN. S. Uekusa, T. Hirano, Meihi University, Kanagawa, JAPAN.

Erbium (Er) -doped semiconductor is a potentially useful material for light-emitting devices in optical communication systems, since the intra-4f-shell transitions of Er ions cause sharp and temperature-stable luminescence in various host materials at 1.54 μm, which corresponds to the minimum absorption of silica-based optical fibers. Photoluminescence (PL) from Er^3 in Er-doped narrow band gap semiconductors (e.g. silicon) is a weak and difficult to observe at room temperature (R.T). Gallium nitride (GaN) is a useful host material because it equips the wide band gap and improves the luminescence properties of the Er^3 ions. In this work, we report about the change of the luminescence structure of Er^3 by the dissociation of nitrogen in Er implanted GaN (GaN:Er). The samples used study were undoped epitaxial GaN layer grown on sapphire substrate. Er implantation energy was performed at 400keV, 1MeV with a dose range of 1×10^{15} cm^{-2} at R.T. Furthermore, the ion-implantation technique were changed there Er energy and dose to do the flat profile of Er concentration to the depth of GaN:Er. Following the ion implantation, these samples were annealed at ranging from 1000°C to 1200°C for 30 minutes using a rapid thermal annealing. The PL spectra were exited using the 325 nm line of He-Cd laser at power of 10mW and we measured the temperature dependence of PL intensity at temperature rang from 15K to 300K. From The temperature dependence of the Er^3-related PL intensity, we found that thermal quenching of the luminescence of Er^3 was suppressed by using GaN as a host material instead of Si, and that Er^3 forms at least two Er-N complex centers with N which contribute to the luminescence of Er^3 in GaN:Er.

G6.16
CROSS-SECTIONAL CATHODELUMINESCENCE STUDY IN Ga-POLAR and N-POLAR GaN EPILAYERS. X.L. Du, D.H. Lim, K. Xu, B.L. Liu, A.W. Jia, A. Yoshikawa, Center for Frontier Electronics & Photonics, Chiba University-Venture Business Laboratory, Chiba, JAPAN; K. Takahashi, Teikyo Univerity of Science and Technology, Department of Electronics and Information Science, Yamanashi, JAPAN.

Difference in the defects-formation and/or growth-mechanism between Ga-polar and N-polar GaN epitaxial layers has been studied by using the cross-sectional cathode-luminescence (CL) characterization at both 80 K and room temperature. The CL system was attached in the field emission scanning electron microscope (FE-SEM) so that high-resolution cross sectional CL-images can be taken under low accelerating voltage such as 5 kV. The epilayers were grown on sapphire substrates by MOVPE, and their polarities were controlled by the sapphire nitridation and the trimethyl-aluminum(TMAl) pre-flow just before the conventional two-step growth, and were confirmed with CAICISS. Distinct cross-sectional CL images of GaN epilayers with Ga-polar and N-polar are, for the first time, revealed and explained in the highlight of different growth mechanisms of the epilayers with different polarities. For the epilayers with Ga-polar, their cross-sectional CL images show clear column structure, which is delimited by dark lines along c-direction of the epilayer. These dark lines are originated from the threading dislocations, grain boundaries and nanopipes. Furthermore, two kinds of nanopipes are identified, one of them terminates inside the GaN epilayer, and the other forms open mouth on the surface which is observed as the small pit on the sample surface. As for the GaN epilayers with N-polar, their cross-sectional CL images show quite different characteristics from those with Ga-polar. They are consisted of dark and bright regions instead of column structure. The bright regions are irregular, and their average size depends on the density of dark regions which are related with the defects lying in the epilayer. These defects act as the non-radiative centers, causing weak CL in these local regions. Finally, the difference of microstructures and defects in these two kinds of epilayers is explained according to the different growth mechanisms.

G6.17
CORRELATION OF STRUCTURE AND SPECTRAL EMISSION CHARACTERISTICS OF GaN NANO-ISLANDS. M. Dietrich, A. Hoffmann, Department of Physics, Technical University of Berlin, GERMANY; T. Riemann, J. Christen, Inst. of Exp. Physics, Otto-von-Guericke-University Magdeburg, GERMANY; M. Reshchikov, J. Cui, H. Morkoç, VCU/Department of Electrical Engineering, Richmond, VA.

Wide-band-gape III-nitrides and their related alloys are technologically important for optoelectronic applications in the blue and UV spectral region. In addition ternary and quaternary alloying of GaN and AlN and the advantage of nano-structures are usual methods to reach these emission energy with high quantum efficiency. The purpose of this report to examine GaN nano-islands (NI) in GaN/AlN superlattices (SL) and their dependency of structural characteristics on the spectral emission. A series of samples grown by MBE on sapphire and silicon substrates were analyzed to investigate the influence of tensile and compressive strain on the piezoelectric fields and their influence on the optical properties. Because of high strain at the layer interfaces, NI growth in Stranski Krastanov mode is initialized in the SL submonolayers. The samples were investigated by photoluminescence (PL) spectroscopy, photoluminescence excitation (PLE) spectroscopy and cathodoluminescence (CL). Due to the differences in the design of the samples, we obtained distinct luminescence maxima of high intensity between 3.1 eV and 3.65 eV at 2K corresponding to a NI like transition for the different samples in PL and in CL spectra. Considering the nature of PLE measurements, the NI like emissions are supplied by carriers excited at 3.48 eV and 3.86 eV. Temperature dependent PL measurements show a stable emission of the NI up to a temperature of about 200K. The integral spectra of CL microscopy taken of an area of 4 x 6 μm^2 of the samples show a broad emission with a full width at half maximum of 200-300 meV. A high resolution scan with a CL spectra spot of 50 nm diameter on the same area directly visualizes the decomposition of the broad luminescence line into sharp NI emission peaks with energies depending on the local position. CL wavelength mappings and monochromatic images directly visualize the nano-islands.

G6.18
OBSERVATION OF BAND GAP ENERGY FLUCTUATION OF MICRO-CRYSTALLINE InGaN:Zn. Hisashi Kanie, Kose Sugimoto, Science Univ. Tokyo, Dept of Applied Electronics, Chiba, JAPAN.

This paper describes a study of the range of the fluctuation of gap energy of InGaN:Zn by measuring photoluminescence excitation (PLE) spectra at 77 K. We have been developing synthesis method of GaN and InGaN to apply nitride phosphors to a phosphor for low-acceleration-voltage cathodoluminescent devices. It is well known that MOCVD grown InGaN films tend to have a fluctuation in In concentration which results in a fluctuation of the band gap energy. The PL mechanism in InGaN films is assigned to the annihilation of an exciton at the potential minima caused by the fluctuated band gap potential. We grew InGaN microcrystals emitting intense blue luminescence by a reaction of GaN and In_2S_3 with NH_3 in the range from 850 to 900°C. PLE spectra of the samples grown at various temperatures show two peaks: one peak is located around 3.47 eV, which is attributed to the band gap energy, and the other peak around 3.15 eV, which we attributed to the In localized state level. We did not observed another peak between the two peaks. We had proposed an atomic structure of the localized state based on an isoelectronic trap theory. However, it has been pointed out that in order to justify the isoelectronic trap model, it is necessary to confirm that the order of potential fluctuation of the grown InGaN microcrystal is comparable to that of GaN. It is known that a PLE spectrum is not always compatible to an absorption spectrum. We grew Zn doped InGaN and measured the PLE spectra to estimate the range of energy gap fluctuation of InGaN, because the PLE spectra is regarded as compatible to the absorption spectra for Zn doped InGaN. The shape of measured PLE peaks at around 3.47 eV were comparable to those of Zn doped GaN. We concluded that the order of the band gap energy fluctuation of micro-crystalline InGaN is comparable to that of GaN.

G6.19
THE INFLUENCE OF Si-DOPING IN BARRIER LAYERS ON THE OPTICAL PROPERTY OF InGaN/GaN MQWs. Guanghui Yu[1], Anwei Jia[1,2], Hyung Jae Lee[1], Akihiko Yoshikawa[1,2]. [1]Center for Frontier Electronic and Photonics, Chiba University-Venture Business Laboratory, Chiba, JAPAN; [2]Department of Electronics & Mechanical

Engineering, Chiba University, Chiba, JAPAN; Kiyoshi Takahashi[3], [3]Department of Electronics and Information Science, Teikyo University of Science and Technology, Yamanashi, JAPAN.

In order to study the influence of Si-doping in the barriers on the optical properties, time-resolved photoluminescence (TRPL) measurements at different temperatures from 16K to room temperature were performed to clarify the recombination processes in InGaN/GaN MQWs. The samples were grown by LP-MOCVD on sapphire substrates with different barrier Si-doping levels in the barriers. From the energy dependence of the PL decay time for different barrier Si-doping levels, the band tail depth was found to decrease with increasing the barrier Si doping levels. This indicates that the potential fluctuation in the InGaN wells was decreased due to the effect of Si doping. The energy dependence of decay time measured at different temperatures shows that the transfer effect of carriers to the energy minima formed by the composition and/or thickness fluctuations is ignorable at high temperatures. The anomalous red shift of emission wavelength and also the anomalous increase of decay time for lightly doped samples show that the lightly Si doping decreases the defects density in the wells, resulting in the significant decrease of the nonradiative processes. All these results can be explained using the model of carrier recombination through localized states where the localization depth decrease with increasing Si doping in the barrier.

G6.20
CATHODOLUMINESCENCE AND MICRO-STRUCTURE OF POLYCRYSTALLINE GaN GROWN ON ZnO/Si. Tsutomu Araki, Hidetaka Kagatsume, Hiroaki Aono Yasushi Nanishi, Ritsumeikan Univ, Dept of Photonics, Shiga, JAPAN.

Interests have been attracted recently in optical property of polycrystalline GaN layers. We have demonstrated that polycrystalline GaN layers grown by ECR-MBE on c-oriented polycrystalline ZnO/Si substrates showed stronger photoluminescence than that of single crystalline GaN grown on sapphire substrate[1]. The GaN layers grown on ZnO/Si had c-oriented columnar structure. In this paper, we investigated relationships between optical property and micro-structure of the poly-crystalline GaN layers using CL, SEM and TEM. ZnO was prepared by magnetron sputtering deposition on Si (001) prior to growth. The ZnO was c-oriented polycrystal consisting of many single crystal domains with various a-axis orientations. A low temperature buffer layer of GaN was grown on the ZnO/Si substrates at 450°C for 10-20 min. Following this procedure, GaN layers were grown at 700°C for 2h. The CL images were compared with the SEM images obtained from the same area of the sample, allowing a direct comparison between the optical property homogeneity with its morphological homogeneity. Very strong cathodoluminescence with a peak of 3.45 eV was observed from the GaN layer, which mainly showed columnar structure with a size of 100-200 nm. On the other hand, the intensity of cathodoluminescence from the GaN with few columnar domains was much weaker than that of the GaN layer with columnar structure. The peak energy was found to be blueshifted. The CL image from the GaN layer, in which columnar domains were locally observed, showed a strong contrast between bright domains and a dark background. It is confirmed that these bright regions in the CL images are corresponding to the columnar domains of the GaN layers, by comparing with the SEM images. These results suggest that the columnar domains are responsible for the strong cathodoluminescence from the polycrystalline GaN layers grown on ZnO/Si. [1] H. Tochishita et al. Proceedings of 2nd ISBLLED, Tu-P21 (1998).

G6.21
OPTICAL CHARACTERIZATION OF AlGaN/GaN MQW'S. Ricardo Rocha, Teresa Monteiro, Estela Pereira, Departamento de Física, Universidade de Aveiro, Aveiro, PORTUGAL.

III-nitride semiconductors present nowadays a great potential on fabrication of UV-blue light-emitting devices based on low-dimensional structures. Nevertheless, the mechanisms associated to light emission from multiple quantum wells are still not completely acquainted. Built-in electric fields due to piezoelectric effects and spontaneous polarization in wurtzite AlGaN/GaN are now widely accepted to be responsible for the quantum-confined Stark effect in the QW transition energies[1]. During this work optical measurements were made in two MQW AlGaN/GaN samples grown by MOCVD. From absorption it was determined the bandgap of the AlGaN buffer layer which Al percentage was confirmed by XRD. Also, XRD revealed the periodicy on the quantum wells pack, assuring that there was no deviation on the total thickness of the pair barrier-well. In one sample, the ratio tb/tw (tb - barrier thickness, tw - well thickness) is constant and in the other it differs for each well. PL spectra that confirm these statements are presented. We present other optical studies, such as PLE, temperature-dependent PL and absorption. Excitonic binding energies are found for each case, and we present the dependence of these values for the well thickness. References: 1. N. Grandjean, B. Damilano, S. Dalmasso, M. Leroux, M. Laügt and J. Massies, J. Appl. Phys. 86, 3714 (1999)

G6.22
CHARACTERIZATION OF THE MECHANISM OF ACTIVATION FOR VISIBLE LUMINESCENCE IN RARE-EARTH DOPED CRYSTALLINE AND AMORPHOUS AlN THIN FILMS. C.M. Spalding, M.L. Caldwell, V.I. Dimitrova, A.L. Martin, M.E. Kordesch, H.H. Richardson, P.G. VanPatten, Condensed Materials and Surface Science Program, Ohio University, Athens, OH.

Rare-earth (RE) doped semiconductors have generated considerable interest as possible materials for applications in light emitting devices with a recent focus on III nitrides because of their superior electro-optical, thermal, and chemical properties. Most of the work in this area has concentrated on crystalline or polycrystalline GaN but recently visible emission has been reported from amorphous III nitride materials doped with Er and Tb. AlN has a wider bandgap than GaN and an Er doped amorphous AlN phosphor material has even been used in an ACTFEL device. Unfortunately, luminescence is not observed from the native grown doped III nitride material (either crystalline or amorphous) and a high temperature activation step is required to induce visible luminescence. The mechanism of activation in both crystalline and amorphous AlN will be studied with photoluminescence (PL), cathodoluminescence (CL), and secondary ion mass spectrometry (SIMS). Crystalline AlN offers higher carrier mobilities and lower phonon scattering over the amorphous counterpart. The effect that defect densities have upon the luminescence yield will be addressed by comparing the CL yield of amorphous films to higher symmetry materials.

G6.23
SHALLOW-IMPURITY-RELATED PHOTOLUMINESCENCE IN HOMOEPITAXIAL GaN. V. Kirilyuk, A.R.A. Zauner, P.C.M. Christianen, J.L. Weyher, P.R. Hageman, P.K. Larsen, Research Institute for Materials, University of Nijmegen, Nijmegen, THE NETHERLANDS; M. Zielinski, Institute of Physics, Polish Academy of Sciences, Warsaw, POLAND.

It has been recently recognised that polarity of GaN is very important for the properties of group-III-nitride heterostructures used for high frequency/high power electronics. Although material and optical properties of GaN of both polarities are of great interest, the most attention has been paid to the Ga-polar layers. This contribution reports on a comprehensive study of shallow-impurity-related photoluminescence (PL) in homoepitaxial N-polar GaN films. The observed PL features are correlated to the compositional properties of the samples as derived from Secondary Ion Mass Spectrometry (SIMS) analysis. GaN epitaxial layers grown on *misoriented* N-polar GaN substrates reveal a high optical quality [1] showing A and B free exciton transitions in addition to narrow bound-exciton peaks (line width < 1 meV). This is in contrast to a broad PL emission from exact N-polar films manifesting a high free carrier concentration. Indeed, the SIMS analysis reveals much higher oxygen concentrations in the exact N-polar layers as compared to the misoriented samples. It is therefore concluded that oxygen is the dominant shallow donor present in the exact N-polar films and responsible for the observed high free carrier concentration. SIMS depth profile measurements suggest that the enhanced concentration of oxygen in the epitaxial films is caused by diffusion from the unintentionally n-doped substrate [2] into the epilayer. These results are also consistent with previously observed Mg contamination of Ga-polar homoepitaxial layers grown on similar single crystal substrates that were strongly compensated with Mg. 1. V. Kirilyuk, et al., Appl. Phys. Lett. 76, 2355 (2000). 2. I. Grzegory, et al., Mater. Res. Soc. Symp. Pros. 482, 15 (1998).

G6.24
Transferred to G5.4

G6.25
TIME AND SPATIALLY RESOLVED MICRO-PHOTO-LUMINESCENCE STUDIES OF GaN FILMS. G.E. Bunea, M.S. Unlu, B.B. Goldberg, Boston Univ, Dept of Physics and Electrical and Computer Engineering and Photonics Center, Boston, MA.

Time and spatially resolved micro-PL studies have identified the presence of hydrostatic strain associated with point defects in a 58 μm thick epitaxial lateral overgrowth (ELO) GaN film. A diffraction limited microscope with a Sapphire solid immersion lens (SIL) was used to obtain a spatial resolution better than 200 nm, while maintaining temporal resolution less than 65 ps and spectral resolution less that 0.6 Å. The sample studied was grown on a 5 μm GaN buffer deposited on c-plane Sapphire substrate by HVPE via a ZnO pretreatment. A 200 nm SiO_2 film was deposited using a pyrolytic reaction of silane and oxygen. A grading consisting of 2 μm wide linear window openings, repeating every 40 μm, was patterned

using standard UV photolithographic techniques and CF_4 reactive ion etching. The ELO portion of the film was grown out of the openings and over the SiO_2 masked regions to an average of 58 μm. The surface of each island exhibits an anisotropic curvature due to wing tilting of the c-axis, yielding an average 4% less thickness of ELO material than as-grown material in the mask openings. Micro-Raman spectroscopy shows no significant change in the biaxial compressive strain in the as-grown region and ELO one. However, micro-PL measurements exhibit a strong red shift (4-5 nm) in the band edge emission of the overgrown material with respect to the coherent regions. This is consistent with the presence of hydrostatic strain associated with point defects. Indeed, low temperature micro-PL experiments shows the presence of two different UV peaks, one at 3.463 eV and another at 3.431 eV, whose dominance of the PL spectrum changes as one moves from coherently grown region to the ELO one. Detailed 2D micro-PL and time resolved mapping of the peaks are under way in order to identify the origin of these defects.

G6.26

COMPARISON OF Er^3 PHOTOLUMINESCENCE AND PHOTOLUMINESCENCE EXCITATION SPECTROSCOPY IN IN-SITU DOPED GaN:Er AND Er-IMPLANTED GaN.
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Selective photoluminescence (PL) and photoluminescence excitation (PLE) spectroscopies have been carried out at 6K on the ~1540 nm $^4I_{\frac{13}{2}}$ to $^4I_{\frac{15}{2}}$ emission of Er^3 in $in-situ$ doped GaN:Er grown by molecular beam epitaxy (MBE). [The properties of $in-situ$ doped GaN:RE grown by MBE at UC are reviewed in ref. 1.] The results are compared with selective PL and PLE studies of Er-implanted GaN which have detected several different Er^3 centers and associated PL spectra.[2-5] PLE spectra of the Er-implanted GaN showed that only one of the Er^3 centers could produce detectable emission when excited directly into the $^4I_{\frac{15}{2}}$ to $^4I_{\frac{9}{2}}$ intra-$4f$ shell transitions while most of the other centers were excited by broad-band below gap absorption related to implantation-induced defects. From knowledge of the cross sections of the absorption mechanisms, it was concluded that most of the Er atoms in Er-implanted GaN are in environments that produce the PL spectrum that can be excited by $4f$ absorption.[4,5] Resonant pumping of Er^3 PL at the sharp line peaks of the $^4I_{\frac{15}{2}}$ to $^4I_{\frac{9}{2}}$ intra-$4f$ shell transitions in the $in-situ$ doped GaN excites a ~1540 nm spectrum that closely resembles the $4f$-pumped spectrum of the Er-implanted GaN. However, significant differences in the Er^3 PL spectrum from $in-situ$ doped GaN:Er are observed as a function of excitation wavelength within both the broadened tails of the $4f$ PLE bands and in broad, defect-related, below-gap PLE bands, indicating that there are some significant variations in Er^3 site configuration throughout the sample. Consistent with these observations, pumping by above-gap light simultaneously excites a variety of these Er^3 site configurations as evidenced by a substantial broadening of the observed ~1540 nm Er^3 PL spectrum. 1. A.J. Steckl, J. Heikenfeld, M. Garter, R. Birkhahn, and D.S. Lee, Compound Semiconductor, Vol. 6 (1), pp. 48-52, Jan/Feb 2000. 2. S. Kim, S.J. Rhee, D.A. Turnbull, E.E. Reuter, X.Li, J.J. Coleman, and S.G. Bishop, Appl. Phys. Lett. 71, 231 (1997). 3. S. Kim, S.J. Rhee, D.A. Turnbull, X. Li, J.J. Coleman, S.G. Bishop, and P.B. Klein, Appl. Phys. Lett. 71, 2662 (1997). 4. S. Kim, S.J. Rhee, X. Li, J.J. Coleman, S.G. Bishop, and P.B. Klein, J. Elec. Mats. 27, 246 (1998). 5. S. Kim, S.J. Rhee, X. Li, J.J. Coleman, and S.G. Bishop, J. Elec. Mats. 28, 266 (1999).

G6.27

DEGRADATION OF LUMINESCENCE FROM GaN DURING ELECTRON BOMBARDMENT: EFFECTS OF LOCAL CHARGING ON CHEMISTRY AND STRUCTURE.
G.S. Cargill III, and E.M. Campo, Department of Materials Science and Engineering Lehigh University, Bethlehem, PA; J. Ramer, M. Schurman, I.T. Ferguson, EMCORE Corp., Somerset, NJ.

Recently we found that near-band-edge cathodoluminescence emission decreases with time for some nominally undoped GaN samples. The rate of intensity decrease depends on the incident beam current. It also depends on the size of the area being scanned, which is determined by the magnification used, although the electron beam voltage and current are held constant and similar regions of GaN are being examined. Faster decrease with time occurs with higher beam currents and higher magnifications. The reduced luminescence efficiency persists over at least 24 hour beam-off periods. In this paper we report further investigations of these effects, including effects of beam voltage, the role of local charging, and the nature of local chemical and structural modifications of the material associated with the reduced luminescence.

G6.28

EFFECTS OF EXCITON-PHONON INTERACTION, DIELECTRIC MISMATCH AND ELECTRIC FIELDS ON THE EXCITON BINDING ENERGIES IN IONIC QUANTUM WELL HETERO-STRUCTURES.
Giuliano Coli, K.K. Bajaj, Department of Physics, Emory University, Atlanta, GA.

To calculate accurately the exciton binding energies in III-V nitride based quantum well structures it is crucial to account for two very important competing effects: the strong exciton-phonon coupling, which enhances the electron-hole (e-h) interaction, and the presence of internal electric fields of the order of a few MV/cm [1], which reduces the e-h interaction. Starting from the expression of the e-h potentials for the exciton-phonon interaction by Pollmann and Büttner[2], and for the dielectric mismatch by Kumagai and Takagahara[3], we have derived analytical expressions for the form factor which describes the effective e-h interaction accounting for these two effects simultaneously. The form factor is then used to calculate the exciton binding energies in ionic quantum well structures in the presence of built-in electric fields. The results of our calculations can be summarized as follow: i) the values of the exciton binding energies we calculate using a bulk exciton-phonon interaction, as formulated in Ref.[2], agree very well with those calculated recently by Zheng and Matsuura[4] using an exciton interacting with confined, interface and half-space phonon modes of a quantum well structure. ii) The effect of the exciton-phonon interaction on the exciton binding energy strongly depends on the intensity of the internal electric fields. Different values for the spontaneous polarization have been suggested by theoretical[1] and experimental works[5], and we show that the enhancement of the exciton binding energy cannot be neglected when the fields are as low as those suggested by Leroux et al. in Ref.[5]. iii) The enhancement of the e-h interaction by the dielectric mismatch and the exciton phonon interaction increases the exciton oscillator strength and decreases the in-plane broadening of the excitonic wave-function, thus leading to a more realistic comparison between theory and experiment. iv) Our analytical approach does not involve time-consuming numerical calculations and the form factor that describes the effective e-h potential can be used in calculations based on variational or Green's methods. The extension of out approach to include the effects of many-body interactions on the exciton binding energies will be also discussed. References: [1] F. Bernardini, V. Fiorentini and D. Vanderbilt, Phys. Rev. Lett. 79, 3958 (1997) [2] J. Pollmann and H. Büttner, Phys. Rev. B 16, 4480 (1977) [3] M. Kumagai and T. Takagahara, Phys. Rev. B 40, 12359 (1989) [4] R. Zheng and M. Matsuura, Phys. Rev. B 58, 10769 (1999) [5] M. Leroux et al., Phys. Rev. B 60, 1496 (1999)

G6.29

OPTICAL AND ELECTRICAL STUDIES OF $In_xAl_{1-x}N$ ALLOY FILMS GROWN ON (0001) SAPPHIRE.
Y.V. Danylyuk, M.J. Lukitsch, C. Huang and G.W. Auner, Dept of Electrical and Computer Engineering, Wayne State Univ, MI; R. Naik, Dept of Physics, Wayne State Univ, MI; V.M. Naik, Dept of Natural Sciences, University of Michigan-Dearborn, MI.

A series of $In_xAl_{1-x}N$ alloy films (thickness ~150 nm) with increasing In concentration (~15 % increments) were grown by Plasma Source Molecular Beam Epitaxy (PSMBE) on sapphire (0001) substrates. X-ray diffraction (XRD) measurements confirm a wurtzite crystal structure of alloy films with good crystallinity and lack of alloy segregation. Optical properties such as refractive index and band gap of alloy films were determined using spectroscopic ellipsometry and optical (UV-Vis) transmission, reflection, and absorption measurements. A systematic variation of the properties was seen as a function of In concentration. In addition, both photoluminescence (PL) and Raman scattering measurements are also used to examine $In_xAl_{1-x}N$ alloys to study the correlation between the alloy composition and optical properties. The electrical properties of alloy films including resistivity, and intrinsic carrier concentration and mobilities (determined by Hall effect), will also be presented.

G6.30

OPTICAL SPECTROSCOPY OF GaN AND $Al_{0.14}Ga_{0.86}N$/GaN SUPERLATTICE DOPED WITH EUROPIUM AND PRASEO-DYMIUM.
H.J. Lozykowski, W.M. Jadwisienczak, School of EECS, and Condensed Matter & Surface Sciences Program, Ohio University, Athens, OH; J. Han, Sandia National Labs, Albuquerque, NM; I.G. Brown Lawrence Berkeley National Labs, University of California, Berkeley, CA.

The study of photoluminescence (PL), PL excitation spectroscopy, PL and CL kinetics and depth-resolved CL was performed on GaN and $Al_{0.14}Ga_{0.86}N$/GaN superlattice implanted with Eu^{3+} and Pr^{3+} ions. The sharp characteristic emission lines corresponding to Eu^{3+} $4f^6$ and Pr^{3+} $4f^2$ intra-$4f^n$-shell transitions are resolved in spectral range from 350 to 1000 nm, and observed under photons (PL) and electrons (CL) excitations, over temperature range 8 - 330 K. The recorded

spectra show europium dominant transitions $^5D_0$-$^7F_{1,2,3}$, and praseodymium $^3P_0$-$^7F_{2,3}$, $^3P_1$-$^3F_3$ respectively. All observed transitions are weakly temperature dependent. The intensity of Eu^{3+} emission from $Al_{0.14}Ga_{0.86}N$/GaN superlattice annealed in N_2 is stronger (~58%) than from Eu^{3+} in the GaN layer, whereas for superlattice doped with Pr^{3+} ions, and annealed under the same conditions, the Pr^{3+} emission intensity was found slightly reduced comparing with Pr^{3+} in the GaN epilayer. Finally the excitation mechanism and quenching processes will be discussed. The results indicate that rare earth doped GaN epilayers and $Al_{0.14}Ga_{0.86}N$/GaN superlattice are suitable as materials for visible photonics devices.

G6.31
SYNTHESIS, STRUCTURE, AND LUMINESCENCE OF A2B4C5 NITRIDES. Vyacheslav Bondar, Lev Axelrud, Vladimir Davydov, Lviv National Univ, Dept of Physics, Lviv, UKRAINE; Tom Felter, Lawrence Livermore National Laboratory, CA.

In order to extend the possibilities of doping of nitrides with RE activators of different valent and coordination states the complex A2B4C5 nitrides were investigated. The crystallochemical computer simulation of the new phosphor materials based on Mn, Ti and Eu-doped nitrides A2B4C5 was made. Methods of synthesis of CaSiN2, CaGeN2, MgSiN2, and MgGeN2 were developed, and X-ray diffraction analysis of them was carry out. It was found that ZnGeN2 compound may be considered as the deformed wurtzite structure with lattice parameters close to GaN. The A2B4C5 compounds extend the possibilities of isovalent substitution at persistent tetrahedral coordination of atoms. The following types of activation with luminescent dopants are possible in CaGeN2 crystal structure: isomorphic substitution of Ca atoms for Eu2+; isomorphic substitution of Ge by Ti4+; heterovalent substitution of Ca atoms by rare earth elements with formation of the defect Ca atoms sublattice of type Ca0.55GeN2. CaSiN2 and MgSiN2 nitrides with more complex structure give the possibility to introduce the activator atoms into the cavities of cross-linked (CaSiN2) or layer (MgSiN2) structure that is formed from the pairs of similar [MgN4] and [SiN4] tetrahedrons. Spectra of cathodoluminescence of phosphors based on Mn-, and Eu-doped nitrides A2B4C5 were investigated. The synthesized samples of CaSiN2, CaSiN2-Mn phosphors showed cathodoluminescence at 640 nm. and at 606 nm., respectively. Maximum of cathodoluminescence spectrum of MgSiN2-Mn is observed in the region of 640 nm. and MgSiN2-Eu phosphor showed cathodoluminescence at 630 nm. Intensities of ESR lines with g=6.0 and g=2.0 indicate on the introduction of Mn2+ and Eu2+ ions both in low-symmetry and high-symmetry positions of MgSiN2 lattice with isomorphic substitution of Mg2+.

G6.32
DEFECT-RELATED LUMINESCENCE IN AlGaN ALLOYS. Hideo Kohno, Henning Feick, Yihwan Kim, and Eicke Weber, Department of Materials Science and Engineering, University of California, Berkeley, CA; Hongxing Jiang and Jingyu Lin, Department of Physics, Kansas State University, Manhatten, KS.

AlGaN alloys are employed in various ways in the large number of currently emerging device applications based on the group-III nitride semiconductor family. Examples are solar-blind detectors, 2-dimensional electron gas-based field-effect transistors, heterojunction bipolar transistors, and charge blocking and/or cladding layers in LEDs and laser diodes. It is important to gain more knowledge about growth-induced defects in AlGaN alloys, as they could easily compromise device performance. So far, defects in AlGaN have been poorly investigated. We have analyzed defect-related luminescence bands in three MOCVD-grown AlGaN samples with AlN molar fractions of 0.24, 0.28, and 0.33. Both cathodoluminescence (CL) and photoluminescence (PL) was studied. The depth distribution of the defect luminescence was determined throughout the 1.3 μm thick layers with CL by varying the energy of the electrons impinging on the sample from 4 to 20 keV. PL was excited with below-band gap light at 3.8 eV using a 325-nm HeCd laser. Both CL and PL were studied as function of temperature in the range between 20 K and 300 K. Finally, luminescence in the near infrared was investigated at 20 K using a 514.5 nm Argon-ion laser for the excitation. In all samples we observe a broad yellow/green luminescence band centered at 2.5 eV as well as other defect-related luminescence lines about 0.5 eV below the band edge of the respective alloy. The latter luminescence band is strongest close to the substrate-epilayer interface and becomes very weak for excitations closely below the surface in all samples. However, study of the temperature dependence of the defect luminescence indicates qualitative differences between the corresponding luminescence centers. In the sample with the strongest defect luminescence we also find a sharp zero-phonon line at 0.86 eV in the near-infrared region. The results are discussed in terms of both stoichiometry-related and metal contamination-related defects.

G6.33
DEVELOPMENT OF AlN BASED UV DETECTOR FOR SPACE APPLICATION. Feng Zhong, Changhe Huang, Jie Xu and Gregory W. Auner, Department of Electrical and Computer Engineering, Wayne State University, Detroit, MI.

AlN is a great promising UV sensing material suitable for space application such as exoatmospheric solar blind detectors due to its large band gap (6.2 ev), excellent radiation and thermal stability. A novel double layer UV detector imaging array based on AlN on Sapphire was developed. The sensing area has 58*58 pixels for UV imaging application. AlN epitaxial layers were grown by Plasma Source Molecular Beam Epitaxy (PSMBE). The quality of AlN thin films were characterized by in-stu Reflection High Energy Electron Diffraction (RHEED), X-Ray diffraction and Atomic Force Microscope (AFM). Standard photolithography and etching processes were applied to fabricate the detector. Experimental results show that the performance of the detector is strongly related to the crystalline quality of AlN thin films. In addition, etching process also improve the sensibility of the detector array.

G6.34
OPTICAL AND STRUCTURAL STUDY OF ION IMPLANTATION DAMAGE IN GaN. A. Suvkhanov, LSI Logic Corporation, Santa Clara, CA; N. Parikh, University of North Carolina at Chapel Hill, Chapel Hill, NC; J. Hunn and D. Poker, Metals and Ceramics Div., ORNL, Oak Ridge, TN.

Doping of GaN with Mg during growth allows one to achieve hole concentrations of ~10^{17}-10^{18} cm^{-2}. The alternative doping process is ion implantation. But this process is accompanied with generation of radiation defects and crystal's non-stoichiometry. The post-implantation annealing at the temperatures, required for defects recovery and impurity activation is accompanied with GaN crystal sublimation. The goal of experiment was to study the generation of radiation defects in GaN under various implantation temperatures. Influence of the radiation defects on optical and structural properties was investigated by means of spectroscopic ellipsometry (SE) photoluminescence (PL) and Rutherford backscattering spectroscopy (RBS). Quantitative correlation of both techniques was critically studied. N-type GaN films grown on SiC with carrier concentration of ~10^{16} cm^{-3} were implanted with 80 keV Si ions and 100 keV Mg ions. Implantation dose varied between 5x10^{14} cm^{-2} and 7x10^{15} cm^{-2}. One set of GaN samples was implanted at liquid nitrogen temperature (LNT). Another set of GaN samples was implanted at room temperature (RT). The third set of GaN samples was implanted at 1000K. Preliminary analysis of obtained data strongly suggests that (a) the process of defects formation during Si ion implantation into GaN is more sensitive to the implant temperature compare to the Mg ion implantation, (b) ion implantation at temperature about 100-250°C is the optimal condition for GaN ion implantation without capping layer, and (c) the position of the emission peak of ion implanted GaN LED does not depend on the implant temperature. The same time an intensity of the mission varies with the temperature of the substrate during implantation.

G6.35
OPTICAL PROPERTIES OF GaAsN SINGLE LAYERS AND GaAsN/InAs/GaAs SUPERLATTICES STUDIED BY SPECTROSCOPIC ELLIPSOMETRY. Gunnar Leibiger, Volker Gottschalch, Faculty of Chemistry and Mineralogy, University of Leipzig, Leipzig, GERMANY; Bernd Rheinlaender, Alexander Kasic, Faculty of Physics and Geoscience, University of Leipzig, Leipzig, GERMANY; Jan Sik, Mathias Schubert, Center for Microelectronic and Optical Materials Research, and Department of Electrical Engineering, University of Nebraska-Lincoln, Lincoln, NE.

Spectroscopic ellipsometry (SE) is employed to study the optical properties of tensile (compressive) strained $GaAs_{1-y}N_y$/(InAs)/GaAs [0% < y < 3.3%] superlattices and $GaAs_{1-y}N_y$ [0% < y < 3.7%] single layers for photon energies from 0.75 eV to 4.5 eV and for wavenumbers from 250 cm^{-1} to 700 cm^{-1}. We use parametric models for data analysis to extract the optical constants of the GaAsN layers as well as the energies of the critical points E_0, E_1, and E_1 Δ_1. We observe the well known redshift of the band-gap energies, and the decrease of the E_0 transition amplitudes, which was theoretically predicted. The energies of the critical points E_1 and E_1 Δ_1 are blueshifted with increasing nitrogen composition. For y < 1.7% this is well explained by the sum of the effects of tensile strain and alloying. In the infrared spectral range we detect the local transverse-optic (TO) lattice resonance of the GaN sublattice at 470 cm^{-1} within the GaAsN SL sublayers and GaAsN single epitaxial layers. The polar strength of the GaN TO mode increases linearly with y, but with different slopes for the GaAsN/GaAs and GaAsN/InAs/GaAs superlattices, respectively. This is due to the different strain states. This effect can be used to monitor strain or nitrogen composition in GaAsN layers. We further detect free carriers in the GaAsN sublayers

of the GaAsN/GaAs superlattices. The absence of free carriers in the InAs/GaAsN sublayers goes along with an improved morphology, which is reflected by a decrease of all broadening parameters and by room-temperature photoluminescence emission.

G6.36
OPTICAL PROPERTIES OF A QUANTUM WELL OF $A_{1-x}B_x$ ALLOY SEMICONDUCTOR IN THE COHERENT POTENTIAL APPROXIMATION. Yuzo Shinozuka, Hirotsugu Kida, Wakayama Univ, Faculty of Systems Engineering, Wakayama, JAPAN; Masanori Watarikawa, Yamaguchi Univ, Faculty of Engineering, Ube, JAPAN.

We have theoretically studied optical properties of a quantum well (QW) in which the well region is constructed from a binary alloy semiconductor $A_{1-x}B_x$ in the coherent potential approximation (CPA). A tight binding model is used for a single particle (electron, hole, Frenkel exciton) in the well which is constructed by a rectangular array of N_xxN_yxN_z sites. A perfect confinement is assumed. Each site is randomly occupied by an A (B) atom with a probability 1-x (x). The system is characterized by the difference in the site energy, Δ=ϵ_A-ϵ_B>0; the transfer energy, t, between nearest neighbor sites; the geometric size of the quantum well (N_x, N_y, N_z); and the concentration x. The coherent potential Σ(E) is assumed to be the same for all sites in the well, and is selfconsistently determined with the average lattice Greens function. The energy density of states ρ(E) shows a symmetry with respect to (x, 1-x) and (E, -E), while the optical absorption spectrum I(hν) does not. For a Slab (∞, ∞, N_z) and Wire (∞, N_y, N_z), ρ(E) is composed of N_z (or N_yxN_z) subbands, each shows the two (one)-dimensional van-Hove singularity. When x (or 1-x) is small, a B (A) impurity-subband always appears at the lower (higher) energy side of each host-subband even for small Δ/t. As x (or 1-x) increases the impurity-subbands become wide and merge into the respective host-subband. The energy separations between subbands are proportional to $1/N_z$ (or $1/N_y$xN_z), then these impurity-host separations are remarkable for thin well width (small N_z (N_yxN_z)). We discuss the optical properties of $In_xGa_{1-x}N$ QW system with special attention to the localization. The effect of the off-diagonal randomness in t and the optical absorption by the inter-subband-transition are also discussed.

G6.37
POLARITY OF GaN THIN FILM PROBED BY X-RAY STANDING WAVE. A. Kazimirov, M.J. Bedzyk, Dept of MS&E, Northwestern Univ; Material Science Division, Argonne National Laboratory; N. Faleev, H. Temkin, Electrical Engineering Dept, Texas Tech Univ, Lubbock, TX; V. Dmitriev, Yu. Melnik, TDI Inc., Gaithersburg, MD.

Reliable determination of the polarity of GaN films grown by different techniques on different substrates presents a challenging experimental problem important for understanding the chemical and physical properties of these films and GaN-based electronic devices [1]. We used the x-ray standing wave technique to determine the polarity of thin crystalline highly perfect GaN epitaxial film on SiC. The film 300 nm thick was grown by hydride vapor phase epitaxy (HVPE) directly on on-axis (0001)Si face of SiC wafer without any buffer layer [2]. The x-ray standing wave was generated inside the thin film using Bragg diffraction from the film [3]. The experiments were performed at the X15A beamline of the National Synchrotron Light Source, BNL. The angular dependence of Ga-K fluorescence was measured while scanning the crystal through the GaN (0002) diffraction peak. The modulation in the fluorescence yield produced by the inward shift of the XSW pattern by half of d-spacing was used to determine polarity. Our results unambiguously show a Ga-polarity of the GaN film, i.e. the film has been grown in the [0001] direction with the upper part of the atomic double layer occupied by Ga atoms. This is opposite to the N-polarity found [4] by the same technique for a film grown by MBE on sapphire. This work was supported by the U.S. DOE under Contract No. W-31-109-ENG-38 and by the NSF under contract No DMR9973436. [1] E.S. Hellman, MRS Internet J. Nitride Semicond. Res.3 (1998) 11; [2] Yu.V. Melnik et al., Diamond and Related Materials 6 (1997) 1532; [3] A. Kazimirov et al., Solid State Comm. 104 (1997) 347; [4] A. Kazimirov et al., J. Appl. Phys. 84 (1998) 1703

G6.38
RAMAN ANALYSIS OF BULK ALUMINUM NITRIDE: TEMPERATURE DEPENDENCE OF THE PHONON FREQUENCIES. J.M. Hayes, M. Kuball, Bristol University, H.H. Wills Physics Laboratory, Bristol, UNITED KINGDOM; Y. Shi, J.H. Edgar, Kansas State University, Chemical Engineering Department, Manhattan, KS.

Micro-Raman scattering measurements were performed on bulk AlN crystals over a temperature range from 10K to 1275K. The temperature dependence of the E_2, A_1(LO), E_1(LO), A_1(TO) and E_1(TO) phonon frequencies closely follows a simple empirical relationship previously introduced for diamond. A temperature-induced frequency shift of the E_2 phonon of $(2.23\pm0.02)\times10^{-2}$/K was determined at high temperatures, which is very similar to values reported for bulk GaN. This suggests that similar parameters will be suitable for $Al_xGa_{1-x}N$ alloys (over the whole compositional range), commonly used in high-power, high-frequency electronic devices. The results, therefore, provide the basis for the non-invasive monitoring of the temperature of $Al_xGa_{1-x}N$ material during growth and processing, or even for creating temperature maps of high-power electronic devices under operation using micro-Raman scattering techniques. Modelling of the temperature dependence of the phonon frequencies considering the crystal lattice expansion and 2-phonon decay contributions gave results in good agreement with the measurements. We will discuss the Grüneisen parameters obtained from the modelling which reflect the dependence of the phonon frequencies on the lattice expansion.

G6.39
OPTICAL STUDIES OF P-TYPE GaN:Mg CO-DOPED WITH OXYGEN. Roman Y. Korotkov, Bruce W. Wessels, Northwestern University, Dept of MS&E, Evanston, IL.

Reactive co-doping is considered to be a most promising technique to achieve high conductivity, high concentration p-type GaN. Mg-doped p-type GaN grown by metalorganic vapor phase epitaxy was co-doped with oxygen donors. Upon co-doping the hole concentration increased to 2 x 10^{18} cm^{-3}. Photoluminescence spectroscopy was used to study the effect of co-doping with oxygen. A deep donor-acceptor (DAP) PL band was observed at 2.4 eV with addition of oxygen. The integrated intensity of the 2.4 eV band decreased by an order of magnitude in comparison to 2.8 eV band typically seen in heavily Mg-doped samples suggesting a reduction in self-compensation. Shifts in position of the photoluminescence band with excitation power and temperature were observed. The band red shifted by as much as 0.3 eV when the temperature was increased from 15 to 150 K. With increased excitation intensity the band blue-shifted by 0.6 eV. The observed PL is attributed to pair DAP emission involving a series of deep donors with energies at 320±30, 600±50, 800±50 meV.

G6.40
X-RAY RECIPROCAL SPACE MAPPING STUDIES OF STRAINED GaN/AlGaN QUANTUM WELLS. O. Briot, S. Ruffenach-Clur, M. Moret and R.L. Aulombard GES, Universite Montpellier II, Montpellier, FRANCE.

GaN/AlGaN quantum wells are currently the subject of considerable investigations, both for their technological potential and theoretical interest. As a matter of fact, strong electric fields are present in these samples, due to both a spontaneous polarization and a piezoelectric polarization. Since piezoelectric effects represent a large part of these effects, it is important to precisely determine and analyze the Aluminum content of the barriers and the strain state of the structure. In this work, we report on the systematic X-ray reciprocal space mapping of a series of GaN/AlGaN samples, with different Al content and well thicknesses. For coherently grown samples, we present a calculation which allow us to precisely determine the strain state and Al content in the samples in one diffraction experiment. In our samples, both GaN and AlGaN are strained, and we discuss the effect of these strains on the band lineups in the heterostructures, and on the amount of electric field due to piezoelectric polarization. We show that the results are perfectly correlated with the energy positions of the excitonic transitions observed in photoluminescence and reflectivity at low temperature.

G6.41
TIME-RESOLVED PL MEASUREMENTS OF GaInNAs MQW STRUCTURES FOR 1.3 μm LDs. A. Kaschner, T. Lüttgert, H. Born, A. Hoffmann, Institute of Solid State Physics, Technical University of Berlin, Berlin, GERMANY; A.Y. Egorov, H. Riechert, Infineon Technologies, München, GERMANY.

GaInNAs is considered a promising material for laser devices with 1.3 or 1.5 μm emission wavelength. Incorporation of In and N into GaAs results in a strong red shift of the emission wavelength. Furthermore, the opposite effect of In and N on the lattice constant arise the possibility to grow GaInNAs lattice matched on GaAs. We investigated four tenfold QW structures with varying N content. Also investigated were two laser structures with 3 stacked QWs, one of which has 50 nm AlAs cladding layers. All samples were grown by MBE. At room temperature, the luminescence varies between 1.1 eV (1.5% N) and 1.02 eV (2.6% N) with FWHMs of 30 meV to 58 meV, respectively. Varying the excitation density from 0.3 W/cm^2 to 300 kW/cm^2, a blue shift of 7 meV is observed. Time-delayed measurements show no red shift with increasing time, denoting piezoelectric fields, if existent, are very weak. Thus, the above-mentioned blue shift can be explained by band-filling effects. The decay times at peak maximum rise from 520 ps (1.5% N) to 760 ps (2.3% N), then drop sharply to 190 ps at 2.6% N. We attribute this to an increased contribution of non-radiative relaxation processes due

to a significantly higher defect density. The laser samples show strikingly different decay times: 340 ps for the uncladded, and more than 2000 ps for the cladded structure. We proved that the thick AlAs layer acts as a trap for rest gas atoms in the growth chamber and therefore reduces non-radiative processes. The results of temperature and time-dependant measurements are discussed to elucidate the nature of the involved radiative and non-radiative processes.

G6.42
GROUP III-NITRIDE BASED VCSEL FOR APPLICATIONS AT THE WAVELENGTH OF 400NM. Maria Linnik, and Aris Christou, Univ of Maryland, Dept of Materials and Nuclear Engineering, College Park, MD.

Short wavelength Vertical Cavity Surface Emitting Laser based on the group III nitrides, GaN, AlN, InN, and their ternary alloys is reported. Optical properties such as band gap and index of refraction of the nitride binary compounds were calculated based on experimental data fitting and first principle calculations. The ternary alloy optical properties were determined in the same manner but based on the binary compound data. The active region containing InGaN strained multiple quantum wells is formed between two Distributed Bragg Reflectors. AlInN/GaN and GaAlN/GaN material systems are shown to be the most suitable for highly-reflective Bragg mirrors with minimized number of layers. $LiGaO_2$ substrate is proposed for GaN growth since it has very small lattice mismatch with GaN (about 0.2%) and it provides a good thermal matching between two materials. We report VCSEL calculations on threshold current and emission spectra.

G6.43
RELATIONSHIP BETWEEN MICROSCOPIC STRUCTURE AND OPTICAL PROPERTY OF POLYCRYSTALLINE GaN ON SILICA GLASS. Hidetaka Kagatsume, Hiroaki Aono, Tsutomu Araki, Yasushi Nanishi, Ritsumeikan Univ, Dept of Photonics, Shiga, JAPAN.

Very strong luminescence has been observed from polycrystalline GaN grown on an amorphous silica glass substrate, although the sapphire and SiC have been mainly used for the practical growth of GaN. This strong luminescence from polycrystalline GaN has attracted much attention in view of the application to large area, low cost optical devices. However, the mechanism of this strong luminescence is not fully understood. We have suggested that the optical property is closely related to the structure of polycrystalline GaN[1]. In this study, we demonstrate the recent results obtained from careful examination on the relationship between microstructure and luminescence from polycrystalline GaN grown on silica glass, by using scanning electron microscope (SEM) and cathodoluminescence (CL). Samples were grown on the silica glass by ECR-MBE. SEM images showed that polycrystalline GaN had mainly a columnar structure. However, among the samples with columnar structures, there were detailed differences in the feature of the domain, i.e. shape, size and homogeneity. First, we compared the sample that had homogeneous columnar domains with the sample that didn't. It was revealed that PL and CL intensity of the former was much stronger than the latter. The luminescence peak was around 3.4 eV at room temperature, which was apparently due to the band edge emission. The deep level luminescence was not observed. It was also suggested that these two samples had different luminescence characteristics by comparing the SEM and CL images. The sample of the latter revealed that the columnar domain was not dominantly contributing to the total luminescence. As for the relationship between the shape of domain and the optical property, it was found that stronger luminescence was observed in the columnar domains with hexagonal shape and larger size, both in width and in height. [1] N. Murata et al. Jpn. J. Appl. Phys. 37 L1214 (1998)

G6.44
A GENERALIZED ROOSBROECKE-SCHOCKLEY RELATION FOR III-NITRIDES IN FAR-FROM-EQUILIBRIUM CONDITIONS. A.R. Vasconcellos, R. Luzzi, Universidade Estadual de Campinas, Instituto de Física Gleb Wataghin, Campinas, São Paulo, BRAZIL; C.G. Rodrigues, Dept Física e Matemática, Universidade Católica de Goiás, Goiânia, Goiás, BRAZIL; V.N. Freire, Dept Física, Universidade Federal do Ceará, Fortaleza, Ceará, BRAZIL; J.A.P. da Costa, Dept. Física, Universidade Federal do Rio Grande do Norte, Natal, Rio Grande do Norte, BRAZIL.

Large gap semiconductors of the III-Nitrides family are presently receiving particular attention due to their technological applications in blue/UV light emitting diodes and diodes lasers. The properties of far-from-equilibrium carriers in these systems are a matter of interest since the knowledge of their evolution to the steady state is very important for the design improvement of their devices. Recently, heating of photogenerated electrons and holes in highly excited GaN epilayers was probed, indicating different patterns of energy dissipation for both [1]. On the other hand, hot electron relaxation in n-type GaN was shown to be dominated by longitudinal optical (LO)-phonon emission with relaxation time as small as 0.1 ps [2], which highlight the role of the nonequilibrium statistical mechanics for the description of the carriers dynamics in GaN. In this work, we consider the behavior of the absorption coefficient $\alpha(\omega)$ and luminescence spectrum $I(\omega)$ in the steady state when III-nitrides (compounds GaN, AlN and InN) are in far-from-equilibrium conditions created by an electric field. Particularly, we analize the higher frequencies part of their spectrum and derive a generalization of the Roosbroecke-Shockley relation $\Lambda_{RS}(\omega, E_F)$, the reason between the frequency dependent luminescense spectrum and absorption coefficient, for nonequilibrium conditions which are dependent of the electric field intensity E_F. We show that the carrier's temperature within a small error is proportional to $|dln\Lambda_{RS}(\omega,_F)/d\omega|$. In conclusion, we can say that optical experiments allow for the characterization of the nonequilibrium macroscopic state of doped III-Nitrides, in the condition of being driven away from equilibrium by the action of electric fields.
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G6.45
THE INFLUENCE OF DEFECTS AND PIEZOELECTRIC FIELDS ON QUANTUM WELL LUMINESCENCE IN InGaN/GaN STRUCTURES. D. Cherns, S.J. Henley, A. Bewick, H.H. Wills Physics Laboratory, University of Bristol, Bristol, UNITED KINGDOM.

High spatial resolution cathodoluminescence (CL) studies have been carried out on GaN/InGaN/(0001)GaN single quantum well (SQW) structures in a field emission scanning electron microscope at temperatures down to 8K. Studies of a sample with a 30nm GaN cap and a 1.5nm $In_{0.28}Ga_{0.72}N$ SQW were carried out at 4–6kV to maximise the QW luminescence. Spectra taken from extended areas showed a progressive blue shift in the QW emission from around 460nm at low beam intensities to about 445nm as the beam intensity was increased. This blue shift persisted after the beam intensity was reduced. CL maps showed that the QW emission was reduced close to defects identified as "V-shaped" pits by secondary electron imaging. The CL maps showed structure in regions devoid of surface features where threading dislocations were known to be present. Moreover the spatial resolution was significantly reduced after the blue shift had occurred. By comparing CL maps with transmission electron microscope studies of plan-view and cross-sectional samples, the influence of different types of threading defect on QW luminescence is quantified. The degraded spatial resolution at high beam currents is interpreted as due to an increase in the diffusion length of carriers in the SQW. It is proposed that both this and the spectral blue shift at high beam intensities can be explained by a combination of screening of the piezoelectric field and band filling effects.

G6.46
GRAIN BOUNDARIES AND Ga VACANCIES IN GaN STUDIED BY POSITRON SPECTROSCOPY. J. Oila, J. Kivioja, K. Saarinen, Laboratory of Physics, Helsinki University of Technology, FINLAND; A.E. Wickenden, D.D. Koleske, R.L. Henry and M.E. Twigg, Naval Research Laboratory, Washington, DC.

Epitaxial GaN layers with different grain sizes were studied using a low-energy positron beam. The GaN:Si layers with n=(1.3-3.7)$\times 10^{17}$ cm^{-3} were grown by MOCVD on sapphire substrate. The average grain size, determined by TEM analysis, increased from 0.2 μm to $2-5$ μm with the increasing growth pressure. Positron experiments reveal positron trapping at two types of defects. First, positrons are trapped at native vacancy type defects, identified as Ga vacancies. The data yield direct evidence that the Ga vacancies are in a negative charge state. This observation is in good agreement with theoretical calculations, which predict that Ga vacancies (or associated complexes) are the dominant native acceptor defects in GaN [1,2]. Secondly, at low temperatures the positron annihilation data show positron trapping at shallow traps which contain no open-volume. The positron trapping rate at these shallow traps correlates well with the density of grain boundaries. We thus assign the observed shallow positron traps to dislocations which define the grain boundaries. The concentration of Ga vacancies, however, is independent of the density of these extended defects, indicating that the formation of Ga vacancies does not require the presence of dislocations. [1] J. Neugebauer and C.G. Van de Walle, Appl. Phys. Lett. 69, 503 (1996). [2] T. Mattila and R.M. Nieminen, Phys. Rev. B 55, 9571 (1997).

G6.47
THE ROLE OF FILM COALESCENCE FOR DEFECT

FORMATION AND THERMALLY INDUCED STRAIN IN GaN EPILAYERS. Tim Böttcher, Sven Einfeldt, Stephan Figge, Marc Diessélberg, Rosa Chierchia, Verena Kirchner, Heidrun Heinke, Detlef Hommel, University of Bremen, Inst. of Solid State Physics, GERMANY.

GaN films grown onto sapphire by metalorganic vapor phase epitaxy are commonly under high compressive biaxial stress. This stress is caused by the large thermal mismatch and builds up during cooling from growth to room temperature. It can be released as long as the coalescence of the films is incomplete and the films mainly consist of single independent grains. We have monitored the coalescence by in-situ reflectometry and investigated the strain state at different stages of growth utilizing high resolution X-ray diffraction (HRXRD) and low temperature photoluminescence. The data indicates that as soon as a compact layer has been formed, the strain in the layer remains constant, independent of the film thickness. The observed growth of separate grains onto the nucleation layer furthermore leads to the formation of dislocations at the interfaces where the individual grains meet. The defect structure of compact layers with different coalescence thicknesses has been investigated by HRXRD analysis, showing that mainly edge dislocations are formed at grain boundaries to compensate for the twist between grains. In contrast the screw dislocation density is lower by about an order of magnitude and appears to be independent of the grain size. Accordingly, films with a large coalescence thickness are highly stressed and exhibit a dislocation density down to 5×10^8 cm^{-2}, whereas a small coalescence thickness results in reduced stress and increased defect density. A model describing the dependence on the coalescence is presented, which holds for layers with similar aspect ratio of lateral to vertical growth rate, independent of growth parameters.

G6.48
Abstract Withdrawn.

G6.49
HIGH TEMPERATURE ELASTIC CONSTANT PREDICTION OF SOME GROUP III NITRIDES. Robert R. Reeber and Kai Wang, North Carolina State University, Dept. of Materials Science and Engineering, Raleigh, NC.

Thermoelastic properties are important for modeling thermal residual stresses and optimizing the growth conditions of semiconductor thin films. Thermal expansion of AlN and GaN has been evaluated and predicted by us earlier[1,2]. Here, high temperature elastic constants are estimated empirically from corresponding state relationships and data from other hexagonal Grimm-Sommerfeld compounds. This information together with our earlier thermal expansion data will further improve our abilities for calculating thermal residual stresses in various semiconductor thin films. 1. K. Wang and R.R. Reeber, Mat. Res. Soc. Proc., Vol. 482, 863(1998). 2. R.R. Reeber and K. Wang, J. Mater. Res., 15, 40(2000).

G6.50
PHASE SEPARATION IN MULTIPLE ZnO/C-$Mg_xZn_{1-x}O$ SUPERLATTICE HETEROSTRUCTURES OBSERVED VIA HIGH RESOLUTION TRANSMISSION ELECTRON MICROSCOPY. Alex Kvit, Ajay Sharma, Jay Narayan, North Carolina State Univ, Dept of Materials Science and Engineering, Raleigh, NC; Gerd Duscher, Oak Ridge National Laboratory, Solid State Div, Oak Ridge, TN.

We have synthesized synthesized ZnMgO alloys of wurtzite (Mg content=0.0-0.34) and cubic (Zn content=0.0-0.18) phases using nonequilibrium pulsed laser deposition method. High quality epitaxial films of ZnMgO wurtzite structure have been grown on (0001) sapphire substrates, whereas, epitaxial cubic ZnMgO films were grown on Si (100) with TiN and MgO buffer layers. The epitaxial growth of TiN and MgO involves domain epitaxy where four lattice constants of TiN or MgO match with three of Si substrate across the interface. Using JEOL-2010 field-emission transmission electron microscope equipped with STEM and Gatan image filter, we can perform atomic structure, STEM-Z, electron energy loss spectroscopy and imaging simultaneously. Such studies on the ZnO/$Mg_xZn_{1-x}O$ superlattices provide first direct evidence of phase-separation in the range of 3 nm, which may explain reduced recombination at defects via quantum confinement. Such speculations have been used to explain high luminescence efficiency in GaInN alloys. The experimental results are found to be consistent with model calculations.

G6.51
PREPARATION OF 30×30 mm^2 FREE-STANDING GaN WAFER BY MECHANICAL LIFTOFF AND OPTICAL PROPERTIES IN THE BACKSIDE OF THE FREE GaN BY CATHODOLUMINESCENCE. Hwa-Mok Kim, Tae-Won Kang, Quantum-Functional Semicond. Res. Cen., Dept of Physics, Dongguk University, Seoul, SOUTH KOREA; Jae-Eung Oh, Center for Electronic Materials and Components, School of Electrical and Computer Engineering, Hanyang University, Ansan, SOUTH KOREA.

Free-standing GaN, nearly equal in area to the 30×30 mm^2 wafer, was produced from 300-350 μm thick GaN films grown on sapphire by hydride vapor phase epitaxy. The thick films were separated from the substrate by mechanical polishing liftoff method, using a diamond slurry. After liftoff, the bow is only slight or absent in the resulting free-standing GaN. And we present the results of optical properties in the backside of produced free-standing GaN by cathodoluminescence.

G6.52
MASS TRANSPORT PROCESSES IN THE EPITAXIAL LATERAL OVERGROWTH OF GALLIUM NITRIDE. C.C. Willan, M.E. Coltrin, J. Han, Sandia National Laboratories, Chemical Processing Sciences Department, Albuquerque, NM.

Epitaxial Lateral Overgrowth (ELO) is a useful technique to improve material quality and reduce defects in GaN. In ELO, a mask pattern of dielectric material, usually either silicon nitride or silicon dioxide, is deposited on top of a GaN buffer layer. Further growth of GaN occurs selectively on exposed areas of the underlying buffer layer, and not on the dielectric material. Because GaN growth does not occur on the masked area there are extra precursors available from these regions for GaN growth adjacent to these masked zones. Except for patterns with very small fill-factors (ratio of exposed area to total wafer area), these growth zones utilize the excess precursors with 100% efficiency and experience a growth rate enhancement when compared to the baseline growth rate. One commonly asked question is whether the lateral mass transport of these excess precursors occurs via gas-phase or surface diffusion. We describe an experiment to answer this question for mass transport above the masked regions and mass transport on and above the GaN epilayer. Deep trenches were etched into the wafer prior to the ELO growth, designed to interrupt lateral transport if it were occurring by diffusion along the surface. Growth rate enhancement profiles were virtually identical with and without the presence of the trench features. The results of these experiments show that gas-phase diffusion dominates the growth rate enhancement seen during ELO. This is further quantified by solving 2-D gas transport equations and using these to model experimental results.

G6.53
FLUX CONTROLLED LATERAL GROWTH OF GaN USING AMMONIA MBE. M.R. Hoit, A.M. Dabiran, A. Parkhomovsky, and P.I. Cohen, Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN.

Lateral epitaxial growth of GaN on nitrogen polar, c-plane sapphire by ammonia molecular beam epitaxy (MBE) was evaluated. Patterns of lines arranged in stars were etched in 0.5 micron thick GaN thin films using reactive ion etching. For the lateral growth, conditions were chosen to obtain rates limited by the ammonia flux on the c-plane. However, the direction of the ammonia flux was set to be incident on the surface at a shallow glancing angle so that self-shadowing in the etched stripes modified the ammonia to Ga flux ratio on the side walls. Depending on the stripe position in a star, different Ga:ammonia flux ratios were obtained. Using desorption mass spectroscopy substrate temperatures were then set so that GaN grew on GaN but did not nucleate on sapphire. GaN was then grown and the widths of the stripes vs orientation in the star patterns measured. Lateral growth was observed, with lateral to vertical growth ratios from 5:1 to 20:1. No crystalline anisotropy was observed. In this MBE case, the main feature controlling the growth was the ammonia:Ga flux ratio. Lateral growth was mainly observed on side walls on which there was an excess of ammonia, producing an approximately 10 degree slope. There was little nucleation on the bottom sapphire and little growth on side walls on which there was an excess of Ga. By using this self-shadowing capability of MBE, it appears that on both the side walls and on the top c-plane GaN surface, excess Ga limited the rate of ammonia dissociation. On the side walls however, growth was only limited by the Ga flux allowing a larger fraction of the incident ammonia to be utilized. Growth occurred under conditions of excess ammonia, where nitrogen diffusion is low, indicating that MBE lateral growth is a pendeo-like process.

G6.54
GROWTH AND CHARACTERIZATION OF EPITAXIAL $In_xAl_{1-x}N$ ALLOY FILMS ON (0001) SAPPHIRE. M.J. Lukitsch, G.W. Auner, Dept of Electrical and Computer Engineering, Wayne State University, MI; R. Naik, Dept of Physics, Wayne State University, MI; V.M. Naik, Dept of Natural Sciences, University of Michigan-Dearborn, MI.

A series of $In_xAl_{1-x}N$ alloy films (thickness ~150 nm) ranging in composition from AlN to InN were grown on Sapphire (0001) substrates by Plasma Source Molecular Beam Epitaxy (PSMBE). Variation in In concentration (~15% increments) was achieved by

increasing the rf source power. All alloys, including the AlN film, were grown at the same conditions and low temperature (375°C) as required for InN growth. The six-fold symmetry of the reflection high energy electron diffraction (RHEED) patterns show all films to be of the wurtzite structure. All films exhibited single (0002) peak from X-ray diffraction (XRD) measurements confirming excellent crystallinity, c-plane orientation of the wurtzite structure and lack of alloy segregation. The alloy compositions were also estimated by (0002) XRD peak positions using Vegard's rule. The results of cross-sectional transmission electron microscopy (TEM) measurements of selected films will also be presented to confirm alloy formation without segregation.

G6.55

ETCHING VS GROWTH IN GaN MOLECULAR BEAM EPITAXY. A. Parkhomovsky, A.M. Dabiran, B. Benjaminsson, B.E. Ishaug, and P.I. Cohen, Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN; J. Han, C. Willan, and J.Y. Tsao, Sandia National Laboratories, Albuquerque, NM.

Striking morphological dependencies are observed in the growth of GaN by ammonia molecular beam epitaxy (MBE) on atomically smooth, Ga-polar templates grown by MOCVD. For example, the growth rate depends on surface roughness, with the rate decreasing as the surface smoothens. And it is well known that GaN is much smoother when grown under excess Ga conditions as opposed to excess ammonia. We suggest that this is due to a competition between growth and etching. Because GaN decomposes via a mechanism that desorbs N_2, there is an activation barrier to decomposition. However, under excess ammonia conditions this restriction should be relaxed. In fact, we have observed the etching of MOCVD GaN under an ammonia flux. These templates are atomically smooth showing step trains with 100 nm terraces. After annealing in ammonia at 780°C and 1E-7 Torr, pits are observed, some located at step edges but others within terraces. After a 5 min anneal, the pit diameters were normally distributed with a mean diameter of 33 nm and σ=13 nm, suggesting only one type of dislocation source. The density depends on the anneal time. Subsequently, GaN was grown and then examined with RHEED and AFM. Depending on the growth fluxes, smooth or hillock covered surfaces were obtained. In the latter case the hillock density was about 5% of the pit density. The hillock terrace sizes depended on the flux ratios; they had slopes of about 1.5°. We found that the terrace length in the hillocks decreases and that the hillock number density increases as the V/III ratio is increased. Step flow could be obtained under excess Ga conditions at substrate temperatures near 730°C. This represents a sensitive means to reveal dislocations and allows an understanding of the mechanism of rough growth.

G6.56

MBE GROWTH OF GaN USING AMMONIA OR PLASMA-ACTIVATED MOLECULAR NITROGEN. A.V. Sampath, E. Iliopoulos, A. Battacharyya, T.D. Moustakas, ECE Department, Boston University, Boston, MA.

The growth of III-Nitrides by MBE involves either molecular nitrogen activated by a plasma source or ammonia. High quality GaN films have been grown by both methods. However, significant differences have been reported by various groups regarding the kinetics of growth, surface reconstruction, polarity and optoelectronic properties. In this paper we report on a comparative study of GaN growth in the same MBE system using these two methods. This eliminates uncertainties related to the system geometry or the determination of important kinetic parameters such as substrate temperature, fluxes, etc. The deposition parameter space involves the use of various low or high temperature buffers, variation of substrate temperature from 700 to 950°C and ratio of III/V fluxes spanning from Ga- to N- rich growth conditions. The plasma method involved either an ECR microwave plasma source or a RF source. Smooth films by this method (rms roughness =.5 nm) can only be produced under Ga- rich conditions. Low temperature buffer layers promote growth with the nitrogen polarity, while high temperature buffers promote growth with the gallium polarity. Films with either polarity were doped n-type using Si with free carrier concentration from 10^{15} cm^{-3} to 10^{20} cm^{-3}. Similarly films with either polarity were doped p-type with free hole concentration up to 10^{18} cm^{-3} without requiring post growth annealing. On the contrary, growth with ammonia leads to smooth films under N-rich conditions that is similar to MBE growth of arsenides. The polarity of these films and their ability to be doped n-type or p-type is under current study.

G6.57

MONITORING OF MOLECULAR BEAM EPITAXY OF GaN, AlN AND AlGaN ON SILICON WITH IN-SITU PYROMETRIC INTERFEROMETRY. Sergey A. Nikishin, Sebastien Francoeur, Henryk Temkin, Texas Tech University, Dept of Electrical Engineering, Lubbock, TX.

We show that time-dependent oscillations of the pyrometer reading can be used as an in-situ diagnostic tool for the growth of GaN, AlN, and AlGaN on silicon substrates. A pyrometer with a narrow detection window detects the grey-body radiation emitted from the Si substrate. As the transparent nitride film grows on the substrate, interference effects modulate the intensity of the signal detected by the pyrometer. The period of the oscillations is inversely proportional to the growth rate. In a growth regime where the sticking coefficient of aluminum is equal to one, a detailed analysis of the interference effects yields the refractive index and the absorption coefficient of the layer. The index of refraction can in turn be used for an estimation of the composition of the growing AlGaN film. The data provided by ex-situ measurements, such as x-ray diffraction and ellipsometry, is in excellent agreement with the data obtained from the optical spectra provided by the pyrometer.

G6.58

PLANAR FORCE-CONSTANT METHOD FOR LATTICE DYNAMICS OF CUBIC InN. H.W. Leite Alves, J.L.A. Alves, DCNAT-FUNREI, São João del-Rei MG, BRAZIL; L.M.R. Scolfaro and J. R. Leite, DFMM-IF-USP, São Paulo SP, BRAZIL.

Recently, there is a considerable interest on the physical properties of cubic InN: it is the most promissing material for optoelectronic devices working on the visible range of the electromagnetic spectrum. However, the knowledge of the dynamical properties of InN are rather scarce: the only experimental data known are for the zone-center modes, using the same sample, and, despite that, there are some divergences about the assignment of the transversal optical phonons. In this work, using the Density Functional Theory within the Full Potential Augmented Plane Wave(FPLAPW) method(Wien97 code), we calculated *ab initio* the equation of state, the effective charges and the phonon dispersion along [100] and [111] directions for the cubic InN, including both hydrostatic and uniaxial strains dependence. Our results show that the apparent divergence between the known experimental results is a consequence of hydrostatic effects on the sample due to differences of the used Raman methods.

G6.59

ANALYSIS OF ATOMIC STEPS ON BULK AlN CRYSTAL FACETS. Nikolai Yakovlev, Carlos Rojo, Leo Schowalter, Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, NY.

Growth of bulk AlN single crystals is of significant interest to the III-nitride community for use as a substrate. The AlN crystals studied in the present work were grown using the sublimation - recondensation method described in [1]. The morphology of the crystal facets was measured using atomic force microscopy. It revealed shapes of individual molecular layers and gave new insight into the mechanism of the growth. On (0001) facets, step flow growth is observed. The steps consist of 300 nm segments along $< 1\bar{1}00 >$ directions, which form triangles characteristic of the wurzite lattice. Screw dislocations were found to intersect this face (their density was observed to be $< 10^4$ cm^{-2}). The monolayer steps that form around the dislocations are arranged in spirals rather than triangles. This indicates that the growth is strongly affected either by the mechanical strain of the dislocation or the density of kinks on the steps. Knowing the elastic constants and thermodynamic properties of the AlN crystal, we could estimate microscopic parameters of the growth, such as the activation energy for diffusion along steps (around 0.5 eV) and the critical concentration for nucleation of 1D islands on a proceeding step. We also identified $(11\bar{2}3)$ facets. Their surface consists of goffers, which averaged 50 nm wide, and ran along the $[1\bar{1}00]$ direction. [1] G.A. Slack, T.F. McNelly, J. Cryst. Growth, 42, 560 (1977).

G6.60

SURFACE RECONSTRUCTION INDUCED EPITAXY OF AlN ON Si(111). M. Jenkins, A. Faik, M.-A. Hasan, and M.R. Sardela Jr.[a], C.C. Cameron Applied Research Center & The Department of Electrical and Computer Engineering, University of North Carolina, Charlotte, NC. [a] Materials Research Laboratory, University of Illinois, Urbana IL.

AlN is a direct wide bandgap (6.2 eV) material suitable for applications in UV emission and detection. In addition, it has a close lattice constant to GaInN, which provides a tunable band gap for emission in the blue to red region. Moreover, integration of group III-nitrides with Si would enable optical interconnects and high power device fabrication on Si. In this work, we have demonstrated growth of hexagonal single crystalline AlN(001) on Si(111) using surface reconstruction induced epitaxy. The Si(111)7x7 surface was first passivated by deposition of ~0.3 monolayer (ML) of Al at 650-700°C. Each Al atom bonds to 3 Si atoms on the surface, which give rise to the well-known Si(111)root3xroot3 surface. The well ordered, Al-passivated Si(111)root3xroot3 surface was then used as a template to initiate epitaxial growth of AlN on Si. Without Al passivation, N

would react with the clean Si surface forming amorphous Si_3N_4, which provides a disordered template and prevents epitaxial growth of AlN. The growth was conducted by using an atomic N flux from a RF atomic source, which was fitted with dual ionization chambers to enhance the atomic to molecular nitrogen ratio and to allow operation at lower pressures. The ratio of atomic to molecular N was studied using emission spectroscopy and was correlated to the RF power used. Al was thermally deposited using an effusion cell. Reflection of high-energy electron diffraction (RHEED), high-resolution X-ray diffraction and transmission electron microscopy results confirmed the formation of single crystalline AlN. The results showed that epitaxial growth of AlN depends strongly on the Al/N flux ratio, growth temperature, and the RF power used.

G6.61
HIGH DENSITY PLASMA ETCHING DAMAGE EFFECTS ON CONTACTS TO n-GaN. Rajwinder Singh, Charles R. Eddy, Jr., Theodore D. Moustakas, Boston University, Dept. of Electrical & Computer Engineering, Boston, MA; Hock M. Ng, Bell Labs, Lucent Technologies, Murray Hill, NJ.

The effects of inductively-coupled plasma etching on the quality of ohmic contacts to n-GaN are reported. The high-density plasma etching employs chlorine chemistry and a range of rf bias power levels (incident ion energies). Resulting plasma damage, even at very low power levels, degrades contact ohmicity. At moderate levels of rf bias power the extent of this degradation for nitride layers with lower doping levels (mid-10^{17} cm^{-3}) is far more severe than for nitride layers with higher doping levels. With increased rf bias, the degradation becomes severe in all films studied. Annealing at 700°C rapidly improves the contact quality. Studies of cumulative annealing time, up to 20 minutes, show that the improvement takes place within the first thirty seconds of annealing. The results of attempts to identify the causes of degradation will also be reported, along with AFM, SEM and surface-sensitive photoluminescence studies on the surfaces subjected to high-density plasma etching.

SESSION G7: ELECTRONIC TRANSPORT AND QUANTUM DOTS
Chairs: Bruno K. Meyer and Kentaro Onabe
Wednesday Morning, November 29, 2000
Room 210 (Hynes)

8:30 AM G7.1
OBSERVATION OF THE QUANTUM HALL EFFECT IN HIGH MOBILITY AlGaN/GaN HETEROSTRUCTURES GROWN BY MOLECULAR BEAM EPITAXY. Michael Manfra, Loren Pfeiffer, Kirk Baldwin, David Lang, Julia Hsu and Kenneth West, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; Richard Molnar, MIT, Lincoln Laboratory, Lexington, MA.

We report on the growth and transport properties of a high mobility two-dimensional electron gas confined at the AlGaN/GaN interface grown by nitrogen plasma-assisted MBE on GaN templates prepared by hydride vapor phase epitaxy. The electron mobility in this series of samples exceeds 50,000 cm^2/Vs at a carrier concentration of $2.0x10^{12}cm^{-2}$. Capacitance-voltage profiling shows the unintentional doping level in the as-grown MBE material to be in the mid $10^{14}cm^{-3}$. Magnetotransport studies at low temperature (T=0.3K) yield well-resolved signatures of the quantum Hall effect. The onset of Shubnikov-de Hass oscillations is observed below 2T and the transverse Hall resistance is fully quantized at magnetic fields below 3T. Spin-split Landau levels are resolved at 5T. In addition to magnetotransport data, we discuss our investigation of the dependence of mobility on two-dimensional carrier concentration. Our data suggests that even for these exceptionally smooth and low dislocation density HVPE substrates the interplay of dislocation scattering and interface roughness presently limit the low temperature mobility in our low density ($n_s<6.0x10^{12}cm^{-2}$) AlGaN/GaN heterostructures.

8:45 AM G7.2
HIGH ELECTRON MOBILITY IN FREE-STANDING GaN SUBSTRATES. A. Saxler, D.C. Look[1], S. Elhamri[2], J. Sizelove, and W.C. Mitchel, Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, OH; M. Callahan, D. Bliss, L. Bouthillette, Sheng-Qi Wang, Air Force Research Laboratory, Sensors Directorate, Hanscom AFB, MA; C.M. Sung, Center for Advanced Materials, University of Massachusetts, Lowell, MA; S.S. Park and K.Y. Lee, Samsung Advanced Institute of Technology, Suwon, KOREA. [1]Also at: Semiconductor Research Center, Wright State University, Dayton, OH; [2]Permanent address: University of Dayton, Dept. of Physics, Dayton, OH.

High peak electron mobilities were observed in free-standing c-plane GaN substrates. Two layers, a low mobility degenerate layer and a high mobility bulk layer, were present in these samples. The carrier concentrations and mobilities for the layers were extracted using two methods: 1) magnetic field dependent Hall effect analysis and 2) a simple two carrier model with the assumption that one of the layers is degenerate. The mobility of the bulk layer is found to peak at over 8000 cm^2/Vs at 60K using the magnetic field dependent Hall effect data. Transmission electron microscopy was also used to study the formation of defects, and high-resolution x-ray rocking curve measurements were made.

9:00 AM *G7.3
HIGH MAGNETIC FIELD STUDIES OF AlGaN/GaN HETEROSTRUCTURES GROWN ON BULK GaN, SiC, AND SAPPHIRE SUBSTRATES. W. Knap, E. Borovitskaya, M. Shur, R. Gaska, Rensselaer Polytechnic Institute, Dept of ECSE and CIEEM, Troy, NY; G. Karczewski, B. Brandt NHMFL and Florida State Univ, Tallahassee, FL; E. Frayssinet, P. Lorenzini, N. Grandjean, J. Massies, CNRS-CRHEA, Valbonne-Sophia-Antipolis, FRANCE; J.W. Yang, X. Hu, G. Simin, M. Asif Khan, Univ of South Carolina, Dept of ECE, Columbia, SC; C. Skierbiszewski, P. Prystawko, M. Leszczynski, I. Grzegory, S. Porowski, High Pressure Research Center UNIPRESS, Warsaw, POLAND.

We will present the results of the experimental and theoretical studies of transport properties of two-dimensional electron gas (2DEG) and three-dimensional electrons (that might be responsible for a parallel conduction) in AlGaN/GaN heterostructures grown over high-pressure bulk GaN, sapphire, and insulating SiC substrates. Our calculations will compare 3-dimensional and 2-dimensional low field mobility accounting for polar optical, acoustic, piezoelectric, ionised impurity, and dislocation scattering. The experimental results include the low field Hall measurements, cyclotron resonance measurements, and cryogenic temperature Quantum Hall Effect studies as well as high-temperature characteristics of High Electron Mobility Transistors fabricated on all these substrates. The room temperature high field measurements allow us to clearly separate contributions of a parasitic parallel conduction from 2DEG conduction in all investigated heterostructures. The Quantum Hall Effect measurements are performed in the magnetic fields up to 30 Tesla and temperatures between 2K-80K. This high magnetic field in combination with very high mobilities (over 60,000 cm^2/Vs) in the sample on the bulk GaN substrates allow us to observe very interesting features related both to cyclotron resonance and spin splitting. The temperature dependence of these splittings determines the spin and cyclotron resonance energy gaps and, in combination with cyclotron resonance results, allows us to determine a complete set of 2DEG transport parameters. The quantum and transport scattering times extracted from our measurements indicate that, at low temperatures, the main scattering mechanisms are due to the long-range potentials.

10:00 AM *G7.4
PROGRESS IN THE MBE GROWTH OF GaN AND ITS ALLOYS. J.S. Speck, B. Heying, C. Elsass, P. Fini, D. Green, E. Haus, C. Poblenz, Y. Smorchkova, U.K. Mishra, S.P. DenBaars, Materials and ECE Depts., University of California, Santa Barbara, CA.

Throughout much of the 1990s, state-of-the-art MOCVD-grown GaN materials and devices were markedly better than those grown by MBE. At the time, this was attributed to the relatively low growth temperature of MBE for nitrides (~600 - 800°C) in comparison with MOCVD (1000 - 1100°C) and the immaturity of the nitrogen sources for MBE. In this talk, we review the Santa Barbara work on MBE of GaN and demonstrate the viability of the technique. Currently, the nitride MBE growth is carried out in a dedicated arsenic-free system with the newest generation rf plasma nitrogen sources. To avoid issues associated with nucleation on a chemically dissimilar, lattice mismatched substrate (e.g., sapphire), all MBE growths are carried out on MOCVD GaN/sapphire 'templates'. We show that the MBE microstructure, morphology, and physical properties critically depend on V/III ratio and substrate temperature. Threading dislocations, from the underlying MOCVD layer, play a critical role in the morphology evolution. We find a strong interplay between V/III ration and dislocation-mediated morphologies. Optimal growth conditions are achieved for group III-rich (metal-rich) conditions. The metal-rich growth leads to challenges in minimizing Ga condensation on the substrate surface. By careful flux control, we have now achieved record mobilities both for two-dimensional electron gases (2DEGs) in the AlGaN/GaN system and bulk n-type GaN.

10:30 AM G7.5
ELECTRON SCATTERING MECHANISMS IN AlGaN/GaN HETEROSTRUCTURES GROWN ON BULK GaN CRYSTALS. E. Borovitskaya, W. Knap, M. Shur, R. Gaska, Dept. of ECSE and CIEEM, Rensselaer Polytechnic Institute, Troy, NY; E. Frayssinet, P. Lorenzini, N. Grandjean, B. Baumont, J. Massies CNRS - CRHEA, FRANCE; C. Skierbiszewski, P. Prystawko, M. Leszczynski, I. Grzegory and S. Porowski High Pressure Research Center,

UNIPRESS, POLAND; D. Maude, Grenoble High Magnetic Field Laboratory, FRANCE.

We present the theoretical and experimental studies of transport properties of two-dimensional electron gas (2DEG) in AlGaN/GaN heterostructures. The properties of dislocation free heterostructures grown over high-pressure bulk GaN single crystal substrates are compared with heterostructures grown over sapphire and insulating SiC. The results of this study are used to establish the role of different scattering mechanisms in 2DEG and three dimensional electron gas transport properties. The magnetotransport measurements are performed in a wide range of temperatures (50mK-300K). Two cases are considered i) Low carrier density MBE grown AlGaN/GaN heterostructures for cryogenic temperatures Quantum Hall Effect studies. ii) The high carrier density MOCVD grown AlGaN/GaN heterostructures for high power/temperature operating HFET's Our calculations show that at low temperatures, the electron mobility is primarily limited by ionized impurity scattering and, at high dislocation densities, by dislocation scattering. At high temperatures, the dislocation scattering is less important and polar optical scattering is dominant. The experimental results on low carrier density MBE grown AlGaN/GaN heterostructures and on high carrier density MOCVD grown AlGaN/GaN heterostructures for Heterostructure Field Effect Transistors (on bulk GaN, SiC, and sapphire substrates) confirm these conclusions.

10:45 AM G7.6
PERSISTENT PHOTOCONDUCTIVITY IN A HIGH MOBILITY TWO DIMENSIONAL ELECTRON GAS IN AN AlGaN/GaN HETEROSTRUCTURE. S. Elhamri[a], A. Saxler and W.C. Mitchel Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, Ohio C.R. Elsass, I.P. Smorchkova, B. Heying, E. Haus, P. Fini, J.P. Ibbetson, S. Keller, P.M. Petroff, S.P. DenBaars, U.K. Mishra, and J.S. Speck College of Engineering, University of California, Santa Barbara, CA. [a]Permanent address: Univsity of Dayton, Department of Physics, Dayton, OH.

Temperature-variable Hall and Shubnikov- de Haas effects have been used to study persistent photoconductivity in a high mobility unintentionally doped AlGaN/GaN heterojunction. The structure was grown by rf plasma-assisted molecular beam epitaxy on an n-type GaN template grown on sapphire by metalorganic chemical vapor deposition. At liquid helium temperatures, the measured Hall mobility in this structure was close to 60000 cm^2/Vs. A blue GaN-based light emitting diode was used to illuminate the sample. This illumination resulted in a photocurrent that was persistent. The persistent photocurrent allowed us to vary the carrier density and study the dependence of the mobility on the carrier concentration. Exposing the sample to illumination resulted in an increase in the carrier density. For small increases in the density, the mobility also increased. However, unlike in previous reports by other authors, extended illumination resulted in an increase in the density and a decrease in the mobility. The initial increase in the mobility is attributed to increased screening due to the increase in the carrier density, while the decrease in the mobility may be attributed to alloy scattering. Because of the high quality of the structure used in this study, well resolved Shubnikov-de Haas oscillations were observed in the field range used in this study. The oscillations allowed us to investigate the relationship between the scattering times and the carrier density.

11:00 AM G7.7
PHONON LIFETIMES AND PHONON DECAY CHANNELS IN SINGLE CRYSTALLINE BULK ALUMINUM NITRIDE. M. Kuball, J.M. Hayes, University of Bristol, H.H. Wills Physics Laboratory, Bristol, UNITED KINGDOM; Ying Shi, J.H. Edgar, Kansas State University, Chemical Engineering Department, Manhattan, KS.

Knowledge of the dynamical properties of phonons is important for device engineers to design better and faster devices. The lifetime of longitudinal-optical (LO) phonons in AlN or GaN, for example, can determine hot-phonon effects, which in the case of GaAs have been demonstrated to play a key role in the carrier relaxation. For GaN, A_1(LO) phonon lifetimes and decay channels have been investigated by Tsen *et al.* [Appl. Phys. Lett. **72**, 2132 (1998)], whereas studies on AlN are rather sparse since only very recently high quality AlN has become available.
Single-crystalline bulk AlN was grown using the sublimation-recondensation method. We report on the Raman analysis of the phonon lifetimes and phonon decay channels of the A_1(LO) and E_2(high) phonons on the single crystalline bulk AlN. The temperature dependence of the phonon lifetimes was investigated from 10K to 1275K. Our experimental results show that amongst the various possible decay channels, the A_1(LO) phonons of AlN decay primarily into two phonons of equal energy (Klemens model), most likely longitudinal-acoustic (LA) phonons. AlN is therefore in great contrast to GaN, where a symmetric decay of the A_1(LO) phonon is not possible due to the rather large energy gap between the acoustic and optical phonon branches. For the E_2(high) phonon we find an asymmetric decay into a high-energy and a low-energy phonon. Possible decay channels of the E_2(high) phonon include combinations of E_2(low) and acoustic phonons. Phonon lifetimes of the A_1(LO) phonon and the E_2(high) phonon of 0.75ps and 2.9ps, respectively, were measured at 10K.

11:15 AM G7.8
SITE-CONTROL OF SELF-ASSEMBLING GaN QUANTUM DOTS AND FABRICATION OF SINGLE ELECTRON TRANSISTORS. Koji Kawasaki[1,2,3], Daisuke Yamazaki[1], Kazuo Tsutsui[1,3], Yoshinobu Aoyagi[1,2,3]. [1]Tokyo Inst of Tech, Interdisciplinary Grad Sch of Sci and Eng, Yokohama, JAPAN; [2]RIKEN, Wako, JAPAN; [3]JST-CREST, Wako, JAPAN.

For realization of the quantum logic gates such as 'qubit' or 'controlled not' using the coupled quantum dots, the control of the position, the size and the distance between the quantum dots are required. Coupled GaN quantum dots are good candidate for the realization of logic gates because of rather insensitive nature of the dots to the surface state. We have succeeded in site-control of self-assembling GaN quantum dots by new focused electron beam induced droplet epitaxy technique and fabrication of single electron transistors using GaN quantum dots. After chemical treatments of the epitaxial AlGaN/SiC(0001) substrate, the surface was directly irradiated by a focused electron beam in lattice patterns of which periods were 100 nm in the electron beam exposure apparatus. After thermal cleaning at 600°C for 10 min in the droplet epitaxy system, Ga droplets were formed at 400°C at exactly in the lattice pattern and were annealed at 600°C in NH_3 gas environment for nitridation. The single electron transistors were formed by lift-off processes of Au/Al of electrodes to form a GaN dot channel. GaN dots of which mean diameter is less than 40 nm with a 100 nm period were controlled by changing growth conditions. It was found that the distance between neighboring dots can be also controlled with annealing time up to tunneling length of less than 20 A. So, we can control the position, the size and the distance between the quantum dots by our technique. The transistor with multi-tunneling junction of self-assembling GaN dots fabricated for demonstrations shows Coulomb blockade phenomena even at room temperature. The electrical transport properties of single electron transistors using the site-controlled quantum dots will be also discussed at the presentation.

11:30 AM G7.9
ELECTRIC FORCE MICROSCOPIC STUDY OF SURFACE STRUCTURE AND POLARIZATION EFFECTS IN GaN THIN FILMS. F. Yun, K.M. Jones, M.A. Reshchikov, J. Cui, M.H. Zhang, A. Sun, A. Baski and H. Morkoc, Virginia Commonwealth University, Richmond, VA; P. Visconti, Virginia Commonwealth University, Richmond, VA and Istituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY; R. Molnar, MIT, Lincoln Laboratories, Lexington, MA.

Stress induced piezoelectric field in III-nitride semiconductors and spontaneous polarization induced electric field at the hetero-interfaces along the c-axis induce charge at the interface which is comparable to the free carrier concentration intended by doping. Mixed Ga-polarity and N-polarity within the film will be detrimental to device performance due to additional scattering induced by the field normal to the film surface. Consequently, investigation of the polarization effects is important and timely as nitride semiconductor devices are being contemplated for system applications. By imaging of the electric field gradient or the surface potential by electric force microscopy (EFM) with sub-micron lateral resolution, both a qualitative and a quantitative measure of polarization induced charge distribution across the surface could be obtained. We have conducted an EFM study in a series of samples grown by different techniques and with different polarities. In MBE grown samples, RHEED pattern was used in conjunction with polarity-dependent etching techniques as criteria to determine the polarity and whether inversion domains are present (mixed polarity). In high-quality HVPE samples, uniform Ga-polarity was assumed and verified by etching and EFM. EFM images of as-grown and regressively etched samples should show the evolution of surface charge after chemical etching of different polarities. Surface state density can be calculated by analyzing the barrier energy as a function of the metal work function and semiconductor electron affinity. The role of polarization was addressed by extraction of the second harmonic term from EFM signal. Cross-sectional EFM (XEFM) was used to image the electric field across the hetero-interface in a 2DEG structure, and the origin of the factors affecting field distribution was traced. Details of the experiments in conjunction with inversion domains and other defect structures will be presented.

11:45 AM G7.10
SPATIALLY RESOLVED LUMINESCENCE INVESTIGATIONS ON 2D-InGaN QUANTUM DOTS. M. Dietrich, J.C. Holst, A. Hoffmann, Department of Physics, Technical University Berlin, GERMANY; T.

Riemann, J. Christen, Magdeburg, GERMANY; I. Krestnikov, W.V. Lundin, A.S. Usikov, N.N. Ledentsov, A.F. Ioffe Physical-Technical Institute, St. Petersburg, RUSSIA.

Because of suitable optical characteristics in the green, blue and UV spectral region, GaN and its related alloys became a main material system of semiconductors for optoelectronic applications. To improve devices like blue and green lasers and LEDs, a proper method to rise quantum efficiency and low down current threshold is to take advantage of nano structures. On this basis, we present experimental optical studies on InGaN quantum structures in wurzite GaN on sapphire. InGaN/GaN MQDs (Multi Quantum Dots) were formed by MOVPE submonolayer insertion growth. In order to achieve higher accuracy in spatial resolution, a shadow mask was prepared on the surface of the samples by electron beam lithography and a standard lift-off process. An uncovered center with a diameter as small as 100 nm is framed by a squared $8\mu m \times 8\mu m$ mask of Ti and Pt. These masked samples were investigated using time and spatially resolved photoluminescence (PL) spectroscopy and cathodoluminescence (CL). In CL as in PL we obtained two distinct luminescence maxima of high intensity at 410 and 460 nm wavelength at 2K corresponding to a quantum well-like and quantum dot-like transition. Due to the electrical excitation beam the quantum well-like luminescence is red shifted by 100 meV by scanning across the mask region. This Quantum-confined Stark-shift is not observed for the quantum dot. Furthermore, we report on spatially and time-resolved investigations of the carrier dynamics of the quantum well and quantum dots, respectively. The influence of local electric fields on the relaxation behavior of excitons and free carriers in those low-dimensional InGaN-structures will be discussed in detail.

SESSION G8: SPECIAL SESSION IN HONOR OF PROFESSOR AKASAKI

Chair: Steven P. Denbaars
Wednesday Afternoon, November 29, 2000
Room 210 (Hynes)

1:30 PM *G8.1
RENAISSANCE AND PROGRESS IN NITRIDE SEMICONDUCTORS-MY PERSONAL HISTORY OF NITRIDE RESEARCH.
Isamu Akasaki, Meijo University, High-Tech Research Center, Nagoya, JAPAN.

Wide bandgap group III nitride semiconductors are currently experiencing the most exciting development. High brightness blue and green LEDs are commercialized, and UV and blue laser diodes (LDs), high-speed transistors (TRs) and UV detectors with low dark current, which will be able to operate in harsh environments, have been demonstrated.
Deposition of low-temperature buffer layer consisting of fine crystallites and amorphous-like structure of a few tens of nanometer thickness just before growth of an epitaxial nitride layer on a highly-mismatched substrate (mostly sapphire) opened up the successful path to the dramatic improvement of crystalline quality of nitrides. This dramatic improvement made it possible ot realize p-type nitrides and to control conductivity of n-type nitrides, and to produce high-quality quantum well structures. These achievements have led to all of those devices. Thus, this buffer layer technique has been widely recognized as the key to success. On the other hand, the nitrides thus grown on sapphire still contain $10^9 \sim 10^{10} cm^{-2}$ of dislocations. These dislocations do not affect severely the LED lifetime, but are obstacle for the high-performance LDs, TRs and UV detectors based on nitrides. Recently, great reduction in dislocation density has been achieved. In this paper, renaissance and progress in crystal growth and conductivity control of nitride semiconductors in the last quarter century are reviewed as the groundwork for recently developed high-performance devices.
My personal history of nitride research will also be introduced.

2:00 PM *G8.2
MICROWAVE $Al_xGa_{1-x}N$/GaN POWER HEMT'S.
Lester F. Eastman, Cornell University, Dept of Electrical and Computer Engineering, Ithaca, NY.

Polarization-induced 2DEG density is $\sim 10^{13}/cm^2$ in undoped structures with .3 < x < .4 and with thin, pseudomorphic barriers. With gate lengths in the range of .3 - .5 μm, breakdown voltage is $\sim$100 V for 2 μm gate-drain spacing. Drain current density is $\sim$1 A/mm. Current slump (DC to RF dispersion) is lessened by passivating the exposed AlGaN surface with Si_3N_4 or by exciting with photons whose energy exceeds 2.2 eV. On SiC substrates current leakage becomes substantial at high drain voltage, near pinch off. Pulse power exceeds 6 W/mm at > 30% power-added efficiency at 9GHz for large periphery devices on sapphire. These devices are electrically limited during pulsed operation, but are thermally limited in C.W. operation. On SiC they are electrically limited to as low as 5 W/mm during C.W. operation due to the leakage current. Microwave load-line measurements are used to show the rise in the knee voltage due to current slump in HEMT's on sapphire, and to show the avalanche rise in drain current in HEMT's on SiC. Power performance limits expected and their figure of merit will be presented.
Several co-workers contributed to this research substantially, including: Bruce Green, V. Tilak, J. Smart, J.R. Shealy, H. Kim, R. Dimitrov, W. Schaff, J. Burm, O. Ambacher, T. Prunty and E. Chumbes. Research is supported by ONR MURI contract N00014-96-1-1223, monitored by John Zolper and by industrial grants by Triquint, Sanders, Raytheon, Motorola and GE.
Special acknowledgement is due to Professor I. Akasaki who supplied initial HEMT material over five years ago to substantially help to initiate this research.

3:00 PM *G8.3
OPTICAL PROPERTIES OF III-N QUANTUM STRUCTURES.
Bo Monemar, Linkoping University, Dept of Physics, Linkoping, SWEDEN.

Results from optical measurements of InGaN/GaN and AlGaN/GaN quantum well structures will be presented, for temperatures between 2K and 300 K. The data include photoluminescence (PL), PL transients in the ps and ns ranges, cathodoluminescence(CL), including CL topographs, and micro-PL. The properties are studied as a function of excitation intensity. Apart from the strong influence of polarization fields, perturbations of the ideal MQW structure are studied, such as potential gradients across an MQW stack, and influence of defects like dislocations on the optical spectra and their intensities.

3:30 PM *G8.4
ADVANCED TECHNOLOGY OF EPITAXIAL LATERAL OVERGROWTH (ELO) OF GaN VIA MOVPE OR HVPE.
Kazumasa Hiramatsu, Hideto Miyake, Mie University, Dept of Electrical and Electronic Engineering, Tsu, JAPAN.

Selective area growth (SAG) and epitaxial lateral overgrowth (ELO) of III-nitrides via MOVPE or HVPE has becoming indispensable techniques in the field of nitride-based optical devices to realize GaN templates or substrates with a low density threading dislocation, particularly, which achieves a high performance LD with a high power and a long life time and a high brightness LED with a high external efficiency. To reduce the dislocation density further, many advanced ELO techniques have been proposed and also followed by other methods of an LT-interlayer method, an anti-surfactant mediated dot method etc. Moreover, those techniques are promising for applications to various kinds of devices such as a DFB LD structure, a facet LD structure, a cold cathode with a field emitter, a HFET and a UV detectors with a low reverse bias current, a wave guide, a buried metal gate transistor, etc. [1] Firstly, these recent progress of SAG and ELO and their applications to optical and electronic devices will be presented. [2] Secondly, we introduce one of the advanced ELO techniques, namely, a facet controlled ELO (FACELO) via LP-MOVPE. Here, we focus on a precise control of a facetted GaN structure which is made artificially under appropriate ELO parameters. This technique results in a low dislocation density, of which distribution indicates no dislocation area in a wide region. And we show reduction mechanisms of the dislocation density during the ELO process as well as crystalline and optical properties. [3] Thirdly, we demonstrate an ELO technique using W or WNx stripe mask via MOVPE or HVPE and discuss the possibility of a buried metal gate structure with GaN. Here, in particular, a thermal stability of the mask as well as GaN, the contact properties of W/n-GaN and WNx/n-GaN, and crystalline properties of the ELO GaN layers are presented.

SESSION G9: CHARACTERIZATION AND BANDSTRUCTURE

Chairs: Chris G. Van de Walle and Bo A. Monemar
Thursday Morning, November 30, 2000
Room 210 (Hynes)

8:30 AM *G9.1
GROWTH AND CHARACTERIZATION OF THE GaN UNDERLYING LAYER USED IN BLUE-VIOLET GaN-BASED LASER DIODES ON SAPPHIRE.
Kenji Funato, Shigeki Hashimoto, Katsunori Yanashima, Takao Miyajima, Koshi Tamamura, Toshimasa Kobayashi, Semiconductor Company, CNC, Sony Corporation, Yokohama, JAPAN; Shigetaka Tomiya, Environmental and Analysis Tech. Dept., Sony Corporation, Yokohama, JAPAN; Tomonori Hino, Takeharu Asano, Shiro Uchida, Masao Ikeda, Sony Shiroishi Semiconductor Inc., Miyagi, JAPAN.

Blue-violet laser diodes of a GaN-based material system were grown using metalorganic chemical vapor deposition. A separate confinement heterostructure was grown on the GaN layer on a sapphire substrate. We have achieved continuous-wave operation of the laser diode with a lifetime of more than 500 hours under a constant output power of 20 mW at 25°C. In order to obtain this performance, we have improved the crystalline quality of the GaN underlying layer, that is, we have reduced the dislocation density that may affect the quality of the layers above the underlying layer. In the first stage of the improvement, we grew the underlying layer under various conditions. The growth pressure was varied from 0.9 atm to 1.6 atm. The residual strain in the layers was estimated by measuring lattice constants using x-ray diffraction. The relaxation of the residual strain tends to be suppressed by raising the pressure. Stimulated emission was observed using optical pumping. The threshold power density decreased as the strain increased, suggesting that the strain relaxation process is accompanied by the generation of defects which act as nonradiative recombination centers. According to observation using transmission electron microscopy, the threading dislocation density was reduced less than mid-10^8 cm^{-2} in the layer grown under a pressure of 1.6 atm. In the next stage, we used a epitaxially laterally overgrown GaN layer as the underlying layer. The seed layer for epitaxial lateral overgrowth was grown under a pressure of 1.6 atm. TEM images show that the threading dislocation density is less than mid-10^6 cm^{-2} in the wing region, while it is mid-10^8 cm^{-2} in the seed region. This result implies that the wing region is suitable for having the laser structure fabricated on it. In fact, we realized the above performance by fabricating the laser stripe over the wing region.

9:00 AM G9.2
INTERSUBBAND OPTICAL ABSORPTION IN GaN/AlGaN QUANTUM WELLS IN THE WAVELENGTH RANGE FROM 1.55 μm TO 4.2 μm. Claire Gmachl, Hock M. Ng, S.N. George Chu, Kirk W. Baldwin and Alfred Y. Cho, Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

Intersubband semiconductor quantum cascade lasers have so far been demonstrated in the InGaAs/AlInAs/InP or GaAs/AlGaAs material systems, resulting in emission wavelengths in the mid-infrared. To obtain shorter (< 3.5 μm) wavelengths, a material system with a higher conduction band offset between the active region quantum wells and barriers has to be used. To that aim we are studying GaN/AlGaN heterostructures. As a first step, we have investigated intersubband optical absorption in narrow, 15 - 30 $\AA$ wide, GaN/AlGaN single and coupled double quantum wells. The samples were grown by molecular beam epitaxy (MBE) on sapphire substrate and a GaN or various AlN mole-fraction buffer layer. The barrier AlN mole-fraction was varied from 0.45 to 0.85. Samples were measured in multiple-pass geometry, and also in waveguide configuration. Peak absorption wavelengths ranged from 4.2 μm for 30 $\AA$ wide wells to as short as 1.55 μm for a 13 $\AA$ wide well. The latter is important as it demonstrates that intersubband transitions in the GaN/AlGaN material system can be used to access the communications wavelength range. Modeling shows that a large contribution to the considerable spectral width of the absorption of $\sim$150 meV likely results from monolayer fluctuations. In addition to the composition dependent band-offset, the intrinsic electric fields in the wells and barriers are the determining factors for the shortest possible wavelength.

9:15 AM G9.3
ROLE OF LOCALIZED QUANTUM WELL EXCITONS IN InGaN QUANTUM WELL STRUCTURE CORRELATED WITH MICROSTRUCTURAL ANALYSIS. S.F. Chichibu, University of Tsukuba, Institute of Applied Physics, Tsukuba, JAPAN; T. Sota, Waseda University, Department of Electrical, Electronics, and Computer Engineering, Tokyo, JAPAN; S. Nakamura, Nichia Chemical Industries Ltd., Department of Research and Development, Tokushima, JAPAN.

InGaN QWs are attracting special attention since they serve as an active layer of UV to amber light emitting devices. Optical properties of InGaN QWs are greatly influenced by the internal electric field, F, normal to the QW plane due mainly to the strain-induced piezoelectric polarization. The field induces quantum-confined Stark effect; redshift of the emission peak relative to that of strain-free QW resonance energy and reduced electron-hole wavefunction overlap (oscillator strength). However, it is experimentally clear that InGaN QWs exhibit higher emission efficiency compared to GaN QWs, even at low excitation conditions although the oscillator strength should be reduced. In this contribution, results of static, modulated, and time-resolved spectroscopies in InGaN MQW laser diode structure (lased at 406 nm) will be discussed making a connection with TEM and nano-EDX analysis. The entire MQW structure is fully strained and lattice-matched to thick GaN underlayer. Tthe interface roughness is smaller or comparable to 1ML thickness. However, the EL peak energy was lower by nearly 50 meV than the resonance energy of the QW obtained by ER, PV, or PLE measurements. The average InN mole fraction of the wells is nearly 5.5%, which is estimated by nanoprobe EDX measurement whose beam size is nearly 1.5 nm. However, small comopositional variation from 5.1% to 5.9% is also found. The bandgap energy difference between the two regions is estimated to be about 41-55 meV, taking the composition-dependent bowing parameter (4-6 eV) into account. The value nearly agrees with the Stokes-like shift, and is nearly 60% of the EL FWHM. Moreover, the piezoelectric field is calculated to be 230kV/cm or 150kV/cm depending on the piezoelectric constants used. Therefore the electron and hole energy states are confined in the well. Weak localization of QW excitons occurs as a result of the large bowing parameter.

10:00 AM G9.4
THE EFFECT OF BIAXIAL STRAIN AND CHEMICAL ORDERING ON THE BAND GAP OF WURTZITE InGaN. A.F. Wright, Sandia National Laboratories, Albuquerque, NM; M. van Schilfgaarde, Sandia National Laboratories, Livermore, CA.

We have performed first-principles calculations to examine the effect of biaxial strain and chemical ordering on the band gap of wurtzite $In_xGa_{1-x}N$ in the range $0 \leq x \leq 0.5$. Our results for unstrained, non-ordered alloys are in good agreement with theoretical estimates and measurements on unstrained zinc-blende alloys, but are in poor agreement with recent measurements on strained wurtzite alloys which display significantly lower gaps. Biaxial strain is found to have a non-linear effect on calculated alloy gaps, increasing them for $x < 0.25$ and decreasing them for $x > 0.25$. Chemical ordering along the [0001] direction in strained alloys is found to decrease the band gaps considerably, yielding much better agreement with the measurements. We discuss our results in terms of current theories concerning the optical properties of wurtzite InGaN alloys.

10:15 AM G9.5
THEORY OF FREE EXCITON EMISSION AND ABSORPTION IN WURTZITE GaN. A.V. Rodina, I. Physics Institute, Justus-Liebig University of Giessen, GERMANY; Al. L. Efros, M. Rosen, Naval Research Laboratory, Washington, DC; A. Hoffmann, Solid State Physics Institute, Technical University Berlin, GERMANY; B.K. Meyer, I. Physics Institute, Justus-Liebig University of Giessen, GERMANY.

We describe theoretically the energy structure of free excitons at zero and weak magnetic fields in wurtzite GaN. The theory takes into account the effects of the hexagonal lattice anisotropy and the interaction between exciton states belonging to the different valence subbands. The analytical expressions for the binding energy of excitons connected with the A, B, and C subbands, their effective g-factors and their diamagnetic shifts are derived using second order perturbation theory. The influence of the external biaxial strain, the lattice polarization, and the interaction with radiation field on the exciton transition energies and Zeeman level splittings are analyzed. The theory developed describes reflectance, emission and magnetoluminescence of high quality GaN samples. A comparison with experimental data has allowed us to evaluate the valence band effective masses and the magnetic Luttinger parameter of wurtzite GaN. The importance of simultaneous consideration of all the effects mentioned above in order to properly describe the free exciton optical spectrum in wurtzite GaN is demonstrated in the following observations: 1. The exciton binding energies as well as the separation energy between the n=1 ground and n=2 excited exciton states in GaN differ significantly from the values predicted by the effective exciton Rydbergs. 2. The fine structure of the n=2 excited state of the A exciton results from the combined effects of the anisotropy, the intersubband interaction and the polar interaction with optical phonons. The 2S sublevel of this exciton state has the lowest energy position at zero magnetic field. 3. The effective g-factor of the hole forming the 1S exciton state differs significantly from the g-factor of free holes in the A valence subband due to the intersubband interaction. 4. The polariton description of an exciton is accounted for the fine structure and Zeeman effect of the A exciton ground state.

10:30 AM G9.6
SPONTANEOUS POLARIZATION IN III-V NITRIDES ALLOYS: AN EXAMPLE OF NON-VEGARD BEHAVIOR. Fabio Bernardini and Vincenzo Fiorentini, Istituto Nazionale per la Fisica della Materia (INFM) and Dipartimento di Fisica, Universita di Cagliari, ITALY.

The knowledge of macroscopic polarization in III-V nitrides alloys is a key ingredient in designing MQW's structures of blue-green light emitting devices. So far polarization in alloys was estimated by linear interpolating the values computed for the binary compounds [1], supposing that polarization closely follows a Vegard-like behavior [2]. Electronic properties of alloys (e.g. band gap) are known to show non-linear dependence on material composition, in this respect macroscopic polarization should not be an exception. In this work we have computed, using ab initio DFT and Berry-phase techniques, the spontaneous and piezoelectric polarization of AlGaN, InGaN and

AlInN alloys for various compositions and structures. The results reveal that polarization has a very large bowing, especially in alloys being formed of large-mismatch constituents; in addition the magnitude of the bowing is largely dependent on the microscopic structure of the alloy. A rational for the non-linear behavior of the polarization is given in terms of a microscopic piezoelectric polarization connected to internal strains.
[1] F. Bernardini et al., Phys. Rev. B 56, R10024 (1997).
[2] V. Fiorentini et al., Phys. Rev. B 60, 8849 (1999).

10:45 AM G9.7
UV RAMAN STUDY OF A_1(LO) AND E_2 PHONONS IN InGaN ALLOYS GROWN BY METAL-ORGANIC CHEMICAL VAPOR DEPOSITION ON (0001) SAPPHIRE SUBSTRATES. Dimitri Alexson, Leah Bergman, Robert J. Nemanich, Dept of Physics, NC State University; Mitra Dutta, Michael A. Stroscio, U.S. Army Research Office, Research Triangle Park, NC; C.A. Parker, S.M. Bedair, Electrical and Computer Engineering, NC State University; N.A. El-Masry, Materials Science and Engineering, NC State University; Fran Adar, Jobin Yvon, HORIBA Group, Edison, NJ.

We report on UV Raman spectroscopy of $In_xGa_{1-x}N$ thin films grown on (0001) sapphire substrates using a specially designed metal-organic chemical vapor deposition (MOCVD) reactor. A buffer layer of GaN was grown on each substrate prior to the growth of the InGaN films. The growth temperature of the InGaN layer was between 690°C and 780°C. Eight films were examined in the compositional range $0<x<0.50$. Mid and deep-UV Raman spectroscopy was done with the 325.2 nm line of the HeCd laser and the 244 nm line of a double frequency Ar ion laser. The use of mid and deep-UV excitation lines avoids several problems present with Raman scattering done with visible laser frequencies. Raman scattering experiments, of thin InGaN films, using visible laser frequencies typically provide additional Raman peaks from buffer layers and substrates. In addition, InGaN thin films with low InN concentration emit strong interfering broadband luminescence in the visible region. With UV excitation, the Raman spectral region of interest is well above any emitted photoluminescence. Investigation of the LO phonon-plasmon interaction via the observed ratio of the A_1(LO) and E_2 modes suggests a surface depletion layer. Also, evidence regarding the presence of compositional inhomogeneities and spinodal decomposition in InGaN thin films is presented. The mode behavior of the A_1(LO) and E_2 phonons was also investigated. We have found compelling evidence for one-mode behavior for the A_1(LO) phonon mode, while our data is suggestive of two-mode behavior for the E_2 mode. These results are consistent with the previously found phonon mode behavior in AlGaN alloys.

11:00 AM G9.8
UNIVERSAL BEHAVIOR OF THE PRESSURE COEFFICIENT OF THE LIGHT ABSORPTION AND EMISSION IN InGaN STRUCTURES. P. Perlin, T. Suski, I. Gorczyca, High Pressure Research Center, Unipress, Warsaw, POLAND; B. Damilano, N. Grandjean, J. Massies, Centre de Recherche sur l'Hetero-Epitaxie et ses Applications, CNRS, Valbonne, FRANCE.

The mechanism of the radiative transitions in InGaN structures has been intensively studied for the last 10 years. This remarkable material is characterized by an extremely high radiative efficiency accompanied by a large Stokes shift of the emission spectra and big nonlinear bowing parameter of its energy gap. Since Chichibu et al. [1] has put forward the hypothesis of the existence of In rich quantum dot like regions in InGaN, corresponding carrier localization was frequently called as a reason explaining peculiar behavior of this material. Application of high-pressure is enabling tool to distinguish between the transitions involving extended band states or localized states because they should have very different pressure coefficients. We have studied an influence of pressure on the emission and absorption spectra measured from various types of InGaN structures such as epilayers, quantum wells and quantum dots. While theoretical predictions are that pressure coefficient of GaN and InN bandgap energies are similar (40 and 30 meV/GPa, respectively) the experimental observation is dramatically different. With the increasing In content and thus decreasing emission/absorption energy their pressure coefficients become very weak eventually reaching zero or even slightly negative values! Moreover, we have established that independently on the structure type, the pressure coefficient for a given transition depends uniquely on its characteristic energy. It seems that neither the scale of microscopic In fluctuation nor the quantum carrier localization can play a decisive role in the determination of the pressure coefficient. This observation suggests that this puzzling pressure behavior is an intrinsic properties of InGaN which can be seen as another example of the deviation of this material from model virtual crystal alloy. It is instructive to recall at this point that another strange alloy namely GaAsN is subjected to twofold reduction of its energy gap pressure coefficient with N content not exceeding two percents. 1. S. Chichibu et al. Appl. Phys. Lett. 69, 4188, (1996)

11:15 AM G9.9
PROPAGATION OF EXCITON-POLARITONS IN NITRIDE-BASED MULTIPLE QUANTUM WELLS. Guillaume Malpuech, Alexey Kavokin, LASMEA, University Blaise Pascal, Aubiere, Cedex, FRANCE; Aldo Di Carlo, INFM-Dipartimento di Ingegneria Elettronica, Universita di Roma II, via Tor Vergata, Roma, ITALY.

It is clear now that the interplay between the structural disorder and the propagation effects also called exciton-polariton effects is responsible for most of the features observed in the linear optical spectra of multiple quantum wells (MQWs). The two most spectacular examples of this interplay are the propagation effects observed in the resonant Rayleigh scattering (RRS) of light [1] and the vertical motional narrowing (VMN) effect [2]. The VMN is manifested in the increase of the decay-time of the time-resolved reflection signal that results from the averaging of the disorder potential in a MQW structure by extended exciton-polariton modes that occupy entire the structure. The specifics of GaN-based heterostructures is that the exciton oscillator strength is enhanced by an order of magnitude as compared to the GaAs-based quantum strictures. On the other hand, the disorder in presently available GaN/AlGaN MQWs is much stronger than in GaAs/AlGaAs MQWs. This makes the nitride-based heterostructures particularly attractive for observation of the VMN effect, and study of disorder effects on the exciton-polariton propagation. Here we present a full semi-classical theory of exciton-polariton effects in disordered MQW structures in application to GaN/AlGaN MQWs. Using realistic parameters for the inhomogeneous broadening of the exciton-lines and for the radiative coupling in GaN/AlGaN MQWs, we show that the coherent optical properties of such structures should exhibit pronounced propagation effects in the RRS and pronounced VMN effect [3]. We predict polariton-induced oscillations in the time-resolved coherent optical spectra of GaN/AlGaN MQWs having a period of the order of hundreds of femtoseconds. [1] G. Malpuech, A. Kavokin, W. Langbein, and J.M. Hvam, to be published in Phys. Rev. Lett. [2] J.J. Baumberg, A.P. Heberle, A.V. Kavokin, M.R. Vladimirova, and K. Köhler, Phys. Rev. Lett., 80, 3567 (1998). [3] G. Malpuech and A. Kavokin, App. Phys. Lett. 76, 3049, (2000).

11:30 AM G9.10
TIME-RESOLVED PHOTOLUMINESCENCE MEASUREMENTS OF $In_{0.15}Ga_{0.85}N/In_{0.015}Ga_{0.985}N$ QUANTUM WELLS WITH Si-DOPED BARRIERS. Mee-Yi Ryu, Young Jun Yu, Phil Won Yu, Kwangju Institute of Science & Technology, Dept of Information & Communications, Kwangju, SOUTH KOREA; Eun-joo Shin, Joo In Lee, Sung Kyu Yu, Korea Research Institute of Standards & Science, Optoelectronics Group, Taejon, SOUTH KOREA; Eun Soon Oh, Ok Hyun Nam, Chul Soo Sone, Young Jo Park, Tae Ill Kim, Samsung Advanced Institute of Technology, Photonics Lab, Suwon, SOUTH KOREA.

We have studied the effects of Si doping on the optical properties of $In_{0.15}Ga_{0.85}N/In_{0.015}Ga_{0.985}N$ quantum wells (QWs) by time-resolved photoluminescence (TRPL). Samples consisted of the following epitaxial structure: (i) a 1.4-μm-thick undoped GaN layer, (ii) a three-period QWs consisting of 48$\AA$ undoped $In_{0.15}Ga_{0.85}N$ wells and 100$\AA$ Si-doped $In_{0.015}Ga_{0.985}N$ barriers, (iii) a 0.1-μm-thick undoped GaN capping layer. The barrier Si-doping concentration was varied from 2×10^{18} to 1×10^{19} cm^{-3}. We have employed two kinds of TRPL measurements. The one was measured by time-correlated single photon counting (TCSPC) system. The excitation source is a picosecond mode-locked Ti:sapphire laser. For longer TRPL measurements, a pulsed Nd:YAG laser was used as an excitation source. First, we measured the decay profiles using TCSPC system. The recombination lifetime depends strongly on the Si-doping level in the InGaN barriers, decreasing from ~80 ns to ~20 ns as the doping level is increased from 2×10^{18} to 1×10^{19} cm^{-3}. And for lower Si-doped sample, the background component increases as the emission energy decreases. This means that there exists a much slower recombination decay component. For the decay measurement of a slower recombination component, a ns pulsed laser was used. The slower decay time is decreased from several hundred ns to several tens ns with increasing Si-doping. The recombination lifetime becomes longer with decreasing emission energy, and hence, the emission peak shifts to the lower energy side as time proceeds. It is observed that the shift of emission peak is decreased with increasing Si-doping. We have also measured the stimulated emission peak in the time-integrated PL measurements. The energy difference between the stimulated emission and spontaneous emission is decreased from 168 meV to 54 meV with increasing Si-doping. The results of TRPL can be explained that the Si-doping results in a decrease of potential fluctuations.

11:45 AM G9.11
LUMINESCENC AND STRUCTURAL PROPERTIES OF InGaN EPILAYER, QUANTUM WELL AND QUANTUM DOT SAMPLES USING SYNCHROTRON EXCITATION. K.P. O'Donnell, M.E. White, Dept of Physics and Applied Physics, University of

Strathclyde, Scotland, UNITED KINGDOM; M.J. Tobin, CLRC Daresbury Laboratories, Warrington, England, UNITED KINGDOM.

The present author and his co-workers have argued that the exceptional optical properties of InGaN samples are in fact due to the presence of nanocrystalline InN aggregates (quantum dots and whats), which form spontaneously during growth of InN-GaN solid solutions. Quantum dots (QD) are expected to play an increasing role in the development of future optoelectronic semiconductor devices, thereby repeating, and perhaps excelling, the success enjoyed by quantum well (QW) materials in the 80's and 90's. In addition, the material physics of nanostructures is far from well understood. Recently, a small number of crystal growth teams have developed techniques of nanostructure fabrication, which depend fundamentally on ensuring growth conditions that favour self-organised 'island' growth. As applied to nitrides, self-assembly of 'quantum discs', of radius about 50 nm and 5 nm thick, differing in composition from their surroundings, can be seen as a controlled replication of what happens spontaneously in conventional growth. While the commercial nitride samples are all grown by metallorganic vapour phase epitaxy (MOVPE), quantum discs are often grown using the more sophisticated (and expensive) techniques of Molecular Beam Epitaxy (MBE). This report extends previous studies of luminescence, luminescence decay and local atomic structure of nitride nanostructures to novel samples containing tailored InGaN quantum discs kindly provided by Dr Nicolas Grandjean of CRHEA/CNRS, Valbonne. In order to advance on a broad front, we have carried out a combination of measurements on a small sample set. High resolution confocal imaging and luminescence decay measurements employ the Daresbury synchrotron radiation source both as a tunable excitation machine and as provider of suitably weak, 100 ps pulses with a large pulse-to-pulse delay. The similarities and differences found between the optical properties of 'bulk', 'QW' and 'QD' samples will be described and discussed.

SESSION G10: QUANTUM DOTS AND PHOTO DETECTORS

Chairs: Volker Harle and Shigefusa F. Chichibu
Thursday Afternoon, November 30, 2000
Room 210 (Hynes)

1:30 PM *G10.1
RECOMBINATION DYNAMICS IN NITRIDE QUANTUM DOTS FOR COLORS RANGING FROM THE UV TO THE DARK ORANGE. P. Lefebvre, M. Gallart, A. Morel, T. Taliercio, J. Allëgre, B. Gil and H. Mathieu, Groupe d'Etude des Semiconducteurs - CNRS - Université Montpellier II, FRANCE; N. Grandjean, B. Damilano and J. Massies, Centre de Recherche sur l'Hétéro-Epitaxie et ses Applications - CNRS - Valbonne, FRANCE.

We present time-resolved photoluminescence (PL) studies of group-III nitride based quantum dots, grown by molecular beam epitaxy on sapphire substrates, by using the Stranski-Krastanov growth mode transition. Half-widths at half maximum as small as 0.05 eV are obtained for PL lines at T = 2K. Increasing the growth time decreases the PL energy and drastically increases the PL decay time, as a result of the increasing of the average dot height and of the built-in electric fields. We present samples covering a broad spectral range, from the ultraviolet to the dark orange, with PL decay times covering several orders of magnitude. Time-resolved PL measurements with variable temperature allow us to observe the competitive influence of several mechanisms, not only the usual radiative and nonradiative recombination processes, but also the carrier feeding from random fluctuations, which plays a crucial role in the case of the larger dots.

2:00 PM G10.2
OPTICAL PROPERTIES OF CUBIC GaN QUANTUM DOTS AND COMPARISON WITH HEXAGONAL ONES. Julia Simon, Benoit Bataillou, Fabien Chabuel, Christoph Adelmann, Esteban Martinez-Guerrero, Régis André, Bruno Daudin, Guy Feuillet, Le Si Dang, Guido Mula, Nikos T. Pelekanos, Henri Mariette, Département de Recherche Fondamentale sur la Matiere Condensée, CEA Grenoble, FRANCE, and University J. Fourier, Grenoble, FRANCE.

Self-assembled cubic GaN quantum dots (QD) embedded in AlN have been grown by plasma-assisted molecular beam epitaxy on SiC substrates. Atomic force microscopy and transmission electron microscopy reveal islands of mean height of 1.6nm and mean diameter of 13nm. Cathodoluminescence, time-integrated and time-resolved photoluminescence data on these cubic (ZB) dots are compared with the ones obtained on hexagonal (WZ) self-assembled GaN/AlN QDs. This allows to isolate pure dimensionality effects from the influence of the giant polarization-induced electric field present in the WZ systems. The following conclusions can be drawn from the analysis of our results: (i) the energy position of the ZB QDs emission is always blueshifted with respect to the bulk cubic GaN bandgap energy, even for large QDs, by contrast to the WZ QDs for which an emission at an energy lower than the bulk WZ GaN bandgap energy is observed as due to the presence of a large electric field. (ii) The emission intensity from the QDs samples is insensitive to the temperature, revealing the strong exciton localization in the QDs which induces a reduction of the nonradiative channels by contrast to the quantum well (QW) systems. (iii) When comparing QW and QD samples in the two phases, one finds that the decay times at low temperature for the WZ structures are always longer than the ZB ones. We attribute this to the presence of electric field in the WZ samples. (iiii) For ZB QDs, the decay time increases with decreasing QD size in keeping with a smaller exciton coherence volume, whereas, for WZ QDs, the opposite behavior is observed, namely the decay time decreases with decreasing QD size. This can be explained by the stronger electric-field induced carrier separation in larger QDs.

2:15 PM G10.3
FABRICATION AND CHARACTERIZATION OF MINI-DISPLAYS BASED ON NITRIDE BLUE/UV MICRO-LED ARRAYS. H.X. Jiang, J.Y. Lin, S.X. Jin, and J. Li, Department of Physics, Kansas State University, Manhattan, KS.

Mini-displays comprising 100 pixels (10 x 10) have been fabricated successfully from arrays of individually controlled micro-LEDs based on $In_xGa_{1-x}N$/GaN single quantum well LED structures. These prototype mini-displays were fabricated by inductively coupled plasma (ICP) etching together with photolithography. Each micro-LED (pixie) was a 10 micrometer-diameter microdisk with a 50 micrometer spacing in between[1]. The performance characteristics of individual pixels including I-V and L-I characteristics, turn-on and turn off speeds, emission wavelength and line width, as well as of a mini-display including uniformity of light emission intensity from different pixels, have been measured. Simple images including letters and numbers have been displayed by these GaN mini-displays. Knowledge gained from these prototype mini-displays can be applied to the fabrication of practical (500x500) mini-displays, which have many novel applications including optical communications and inter-board connection. Other applications include mini-displays on portable communication devices and wearable displays for next generation video monitors. The advantages of mini-displays based on GaN micro-LED arrays for wearable displays include higher spatial resolution due to shorter wavelength and full color display capability by energy down conversion to red and yellow colors. 1. "GaN microdisk light emitting diodes", S.X. Jin, J. Li, J.Z. Li, J.Y. Lin, and H.X. Jiang, Appl. Phys. Lett. 76, 631 (2000).

2:30 PM G10.4
AC OPERATION OF GaN:Er THIN FILM ELECTROLUMINESCENT DISPLAY DEVICES. J. Heikenfeld and A.J. Steckl, University of Cincinnati, Nanoelectronics Lab, Cincinnati, OH.

Display devices utilizing thin film electroluminescence (TFEL) of inorganic phosphors require wide bandgap semiconductor hosts with the capability for generation of hot carriers (>2 eV) which can impact excite luminescent centers. We have recently shown[1] that rare earth (RE)-doped GaN phosphors can provide full color capability (using Pr, Eu, Er, and Tm) and high brightness under DC operation. These DC-type devices used GaN:RE films grown by MBE on crystalline substrates.
In this paper we present the first results on GaN TFEL devices designed to be operated under conventional display AC operation. We have fabricated insulator/phosphor-green/insulator layered structures which allow reliable AC-biased high field operation by current limiting the electrical breakdown of the GaN layer. The green phosphor consisted of polycrystalline GaN:Er deposited on an amorphous dielectric layer consisting of one of the following: SiO_2, Si_3N_4, AlN, Al_2O_3. The complete structure used an ITO transparent top electrode and a p^+-Si substrate for bottom electrode. The dielectric breakdown of the insulator layers was greater than 2 MV/cm allowing stable operation at 200 Vp AC bias. The emission spectrum of the AC-type devices was essentially identical to that obtained previously with DC-type devices, with Er^{3+} $4f$-$4f$ green emission lines at 538 and 559 nm. The luminance performance of the AC device was evaluated as a function of AC peak voltage and frequency. For example, at 10 kHz the brightness increased with voltage from 4 cd/m^2 at 65 Vp to 50 cd/m^2 at 170 Vp. At an AC peak voltage of 170 V, the brightness increased linearly with frequency from 5 cd/m^2 at 1 kHz to 50 cd/m^2 at 10 kHz. A brightness of nearly 300 cd/m^2 was obtained at 100 kHz. These devices demonstrate the feasibility of high brightness AC TFEL devices using GaN:RE phosphors deposited on amorphous layers. The possibility of an all-nitride structure (Si_3N_4 or AlN insulators and GaN:RE phosphor) which can be in-situ fabricated is particularly exciting.
1. A.J. Steckl, J. Heikenfeld, M. Garter, R. Birkhahn, and D.S. Lee, Compound Semiconductor, Vol. 6 (1), pp. 48-52, Jan/Feb 2000.

2:45 PM G10.5
GaN OPTOELECTRONIC MESFET. Remis Gaska, Michael S. Shur, SET, Inc., R. Srinavasan, G. Tamulaitis, V. Adivarahan, M. Asif Khan, J.W Yang, Univ South Carolina, Dept ECE.

We report on a GaN optoelectronic MESFET with a transparent Schottky gate. In a regime with a floating drain, this device operated as a photovoltaic detector with a cutoff wavelength of 360 nm and with responsivity on the order of 0.1 A/W. When the drain bias is applied, the device works as a photoconductor detector exhibiting a large photoconductive gain of several thousands. In this regime, a typical detector response time is on the order of tens of microseconds, and the ratio of the photocurrent to the dark current is larger, and the device characteristics depend on the gate bias. Under negative gate bias, the device characteristics change, and, with an increase in the negative gate bias, approach the characteristics corresponding to the photovoltaic mode of operation with a commensurate decrease in gain and increase in speed. Hence, choosing an appropriate gate bias establishes a desired trade-off between gain and speed. We also present a model that relates the photoconductive mode of operation to the hole trapping and to the corresponding shift in the threshold voltage.

3:30 PM *G10.6
PERFORMANCE CHARACTERSTIC OF CW InGaN MULTIPLE QUANTUM WELL LASER DIODES. Michael Kneissl, Xerox Palo Alto Research Center, Palo Alto, CA.

AlGaInN laser diodes are currently undergoing rapid development and the commercialization of violet laser diodes has just recently begun. The reduction of the dislocation density in the GaN material has been shown to be an important factor to improve laser diode performance and lifetime. Although the benefits of low dislocation materials have been clearly demonstrated by the rapid progress in laser diode lifetime, there is still very little known on how other laser properties, i.e. the distributed loss or internal quantum efficiency, are effected by the dislocation density in the material. In this paper we will compare the performance characteristics of cw laser diodes grown by metal organic chemical vapor deposition on sapphire substrates with otherwise identical devices, but fabricated on laterally epitaxially overgrown GaN on sapphire (LEO) substrates. For ridge-waveguide laser devices grown on LEO substrates, room-temperature cw threshold current densities as low as 5.9 kA/cm^2 with emission wavelength near 400 nm have been observed. Under cw conditions, threshold currents were as low as 62 mA with threshold voltages of 7.5 V. CW laser operation was observed up to a heatsink temperature of 70°C. Significant improvements in light output vs. current were observed for devices grown on LEO substrates, with cw output powers greater than 20 mW and differential quantum efficiencies larger than 0.5 W/A. This improved performance can be attributed to the increased internal quantum efficiency and reduced distributed loss in the low dislocation density material obtained with LEO. Thermal effects on the laser diode performance and lifetime will also be discussed and scenarios for improved thermal management will be presented.

4:00 PM G10.7
PHOTORESPONSIVITY OF ULTRAVIOLET DETECTORS BASED ON InAlGaN QUATERNARY ALLOYS. T.N. Oder, J. Li, J.Y. Lin, and H.X. Jiang Department of Physics, Kansas State University, Manhattan, KS.

We describe the growth, fabrication and characterization of ultraviolet (UV) photoconductive detectors based on InxAlyGa1-x-yN quaternary alloys that are lattice-matched to GaN. InxAlyGa1-x-yN quaternary alloys of different In (x) and Al (y) compositions were grown on sapphire substrates by low pressure MOCVD. Films were characterized by different techniques including x-ray diffraction (XRD), Rutherford back scattering (RBS), secondary ion mass spectroscopy (SIMS), energy dispersal system (EDS), scanning electron microscopy (SEM), atomic force microscopy (AFM), Hall-effect, and time-resolved photoluminescence measurements. In (x) and Al (y) composition dependencies of optical and electrical properties of these quaternary alloys have been studied systematically. The detectors consisted of 0.1 mm InxAlyGa1-x-yN quaternary alloys grown on 0.5 - 1.0 mm GaN epilayers. The characteristics of these UV detectors, including the cut-off wavelength, photoresponsivity, and device speed have been measured. With varying In and Al compositions, the cut-off wavelength of the InxAlyGa1-x-yN detectors could be varied to the deep UV range. The most important and intriguing result is that the responsivity of the InxAlyGa1-x-yN quaternary alloy exceeded that of AlxGa1-xN alloy of comparable cut-off wavelength by a factor of five. This makes the nitride quaternary alloys a very important material for solar-blind UV detector applications particularly in the deep UV range where Al rich AlGaN alloys have problems with low quantum efficiency and cracks due in part to lattice mismatch with GaN. Advantages of InxAlyGa1-x-yN quaternary over AlxGa1-xN ternary alloys for UV detector applications will also be discussed.

4:15 PM G10.8
SOLAR-BLIND AlGaN HETEROSTRUCTURE PHOTODIODES. J.D. Brown, J. Li, P. Srinivasan, J. Matthews and J.F. Schetzina, North Carolina State University, Raleigh, NC.

Atmospheric absorption of sunlight by ozone and oxygen gives rise to a narrow wavelength band at the earth's surface from about 240-285 nm that is termed the "solar-blind" UV region. UV detectors that respond exclusively to radiation in this wavelength region are termed "solar-blind" detectors since they can detect objects that emit radiation in this narrow wavelength window without interference from the sun. In this paper, we report the first successful synthesis, fabrication, and testing of a backside-illuminated solar-blind UV detector based on an AlGaN p-i-n heterostructure. The p-i-n photodiode structure consists of a 1.0 μm n-type $Al_{0.64}Ga_{0.36}N$:Si layer grown by MOVPE onto a low temperature AlN buffer layer on a polished sapphire substrate. On top of this base layer is a 0.2 μm undoped $Al_{0.47}Ga_{0.53}N$ active layer and a 0.5 μm p-type $Al_{0.47}Ga_{0.53}N$:Mg top layer. Square mesas of area A = 4 x 10^{-4} cm^2 were obtained by reactive ion etching using BCl_3. Ti/Al and Ni/Au were used for n-type and p-type metal contacts, respectively. Techniques employed to maximize the flow of photocurrent through the high-Al-content heterostructure and the metal/semiconductor interfaces will be discussed using device band structure diagrams. Photodiode spectral responsivities R were measured under zero-bias at 300K for the wavelength range 200 to 500 nm with the devices illuminated through-the-substrate. R_0A values were also obtained for each sample. The detector spectral detectivity D* was then calculated using standard photodiode equations for a noise-limited detector. The solar-blind photodiodes exhibited a very narrow UV spectral responsivity band peaked at 273 nm with a FWHM = 21 nm. Maximum responsivity R = 0.051 A/W, corresponding to an internal quantum efficiency of 27%. R_0A values up to 8 x 10^7 Ω-cm^2 were obtained, corresponding to D* = 3.5 x 10^{12} cm Hz$^{1/2}$ W^{-1} at 273 nm. The solar-blind photodiode structure that has been developed is suitable for the fabrication of backside-illuminated photodiode arrays for use in solar-blind digital cameras. Initial 128x128 and 320x256 solar-blind photodiode arrays are under process. Results of this work will also be reported at the meeting. This work is supported by grants from DARPA and ARO.

4:30 PM G10.9
SOLAR-BLIND AlGaN P-I-N PHOTODIODE ARRAYS. P. Lamarre, A. Hairston, M.B. Reine, M.F. Taylor, A.K. Sood, Sanders-A Lockheed Martin Company, Lexington, MA & Nashua, NH; M.J. Schurman, I.T. Ferguson, Emcore, Somerset, NJ; R. Singh, C.R. Eddy, Jr., Dept. of Electrical & Computer Engineering and Photonics Center, Boston University, Boston, MA.

We are developing 256x256 solar-blind UV Focal Plane Arrays (FPAs). The hybrid UV FPA syructure consists of a 256x256 back-illuminated AlGaN p-i-n photodiode array that is bump-mounted to a matching 256x256 silicon CMOS readout integrated circuit (ROIC) chip. This structure is directly analogous to the hybrid FPAs that have been extensively developed and manufactured for the infrared spectral region, which incorporate back-illuminated photodiode arrays of narrow-gap semiconductors such as InSb and HgCdTe. The first layer in the back-illuminated AlGaN p-i-n device is a silicon-doped n-type AlGaN window layer that serves as the common n-side contact to all the elements in the 256x256 array. The alloy composition of this layer determines the cuton wavelength. The next layer is an unintentionally-doped n-type AlGaN absorber layer, with a smaller band gap than the window layer, that forms an isotype heterojunction with the window layer. The alloy composition of the absorber layer determines the cutoff wavelength. The final layer is a Mg-doped AlGaN p-type layer that forms a p-n homojunction with the n-type absorber layer. The back-illuminated AlGaN p-i-n photodiode has a number of advantages. It operates at zero-bias voltage, so 1/f noise is not an issue. Because the absorber layer is nearly fully depleted at zero bias voltage, quantum efficiencies are high; photocarrier collection does not depend on carrier diffusion, which is an important consideration for a material such as AlGaN in which the diffusion lengths are quite short. Our back-illuminated AlGaN p-i-n mesa photodiode arrays were fabricated from multilayer heterostructure AlGaN films grown by MOCVD onto 2 inch dia. c-plane double-side-polished sapphire substrates. Mesas were etched by the Inductively Coupled Plasma (ICP) process to assure minimal damage at the mesa surface (all previously reported back-illuminated AlGaN photodiodes were etched by RIE methods). Both 256x256 arrays and variable-area diagnostic arrays were fabricated side-by-side on the same film. Cutoff wavelengths for the photodiodes reported range between 280 and 365 nm. This paper will describe the design, growth, fabrication and performance of our back-illuminated AlGaN p-i-n photodiode arrays. Performance data to be presented include

dark current and photocurrent versus voltage, zero-bias resistance and zero-bias resistance-area product, spectral response, quantum efficiency, and capacitance versus voltage. Data will be presented for individual photodiodes as well as for variable-area diagnostic arrays, where the variation of dark current with diode area can distinguish between surface and bulk mechanisms. Mechanisms responsible for various features of the current-voltage characteristics and for the quantum efficiency versus wavelength will be discussed and will be related to device design as well as to starting material and processing characteristics. Our data will be compared to data previously reported for AlGaN p-i-n photodiodes. We will also present performance data for 256x256 UV FPAs formed by hybridizing recently fabricated back-illuminated AlGaN p-i-n arrays to 256x256 silicon CMOS ROIC chips that were originally designed and fabricated by Lockheed Martin for use with HgCdTe photodiode arrays. Data for the quantum efficiency, noise and sensitivity, both average values as well as distributions, for 256x256 UV-FPAs will be presented. This work is being performed as part of the DARPA Solar Blind Detector Program, managed by Dr. Edgar J. Martinez of the DARPA Microsystems Technology Office, under Office of Naval Research Contract N00014-99-C-0138, entitled "Solar Blind Detector Array." The ONR Program Manager is Dr. Yoon-Soo Park.

4:45 PM G10.10
UV DIGITAL CAMERA BASED ON 128x128 ARRAYS OF AlGaN p-i-n PHOTODIODES. J.F. Schetzina, J.D. Brown, J. Li, P. Srinivasan and J. Matthews, Department of Physics, North Carolina State University, Raleigh, NC; Thomas Nohava, Wei Yang, and Subash Krishnankutty, Honeywell Technology Center, Plymouth, MN.

The first successful demonstration of UV focal plane array imagers based on two types of AlGaN heterojunction p-i-n photodiodes that operate in the wavelength range from 280-365 nm is reported. The first diode structure consists of a 1.5 μm $Al_{0.23}Ga_{0.77}N$:Si n-type layer grown by MOVPE onto a low temperature AlN buffer layer on sapphire. On top of this is a 0.2 μm undoped i-GaN active layer followed by a 0.5 μm p-type GaN:Mg layer. This structure produces devices that respond to UV radiation in the 320-365 nm wavelength region when illuminated through-the-substrate. The second type of diode structure consists of a 1.5 μm thick n-type $Al_{0.45}Ga_{0.55}N$:Si layer, followed by a 0.2 μm undoped i-$Al_{0.23}Ga_{0.77}N$ active layer and a 0.5 μm p-type $Al_{0.23}Ga_{0.77}N$:Mg top layer. These devices respond to UV radiation in the 280-320 nm wavelength region. Each of the 128x128 photodiode arrays consist of 16,384 mesa diodes. The mesas are 32 mm squares on a 38 mm pitch, corresponding to a fill factor of 71%. Photolithographically defined Ni was used to define the mesas, and BCl3 reactive ion etching was used to etch the mesas down to the n-type AlGaN base layer. Ni/Au and Ti/Al metallizations, followed by an anneal at 600-700°C, were employed to obtain p-type and n-type ohmic contacts, respectively. The 128x128 diode arrays were hybridized to Si readout integrated circuits (ROICs) using flip-chip bonding techniques in which In bump bonds were employed. The hybridized focal plane arrays (FPAs) were then wire-bonded to leadless chip carriers (LCCs) and inserted into the NCSU UV camera for testing. The UV digital camera employs an adjustable fused quartz lens for focusing the desired UV scene onto the AlGaN FPA, together with readout and testing electronics controlled by computer. The nitride FPA image can be read out from the Si ROIC and displayed real-time at frame rates ranging from 15-240 frames per second – or a sequence of images can be stored by computer as a digital image data set from which a selected frame or sequence of frames can be used to generate digital UV images or movies. A variety of UV imagery in the 280-365 nm region has been obtained using the nitride UV digital arrays. Single-frame visible-blind UV images of alpha-numeric, geometric, and astronomical scenes will be displayed. Digital UV movies of pulsed xenon lamps, UV welding, and flame imagery will also be presented. This work is being supported by grants from DARPA and ARO.

SESSION G11: POSTER SESSION
ELECTRONIC PROPERTIES AND TRANSPORT
Thursday Evening, November 30, 2000
8:00 PM
Exhibition Hall D (Hynes)

G11.1
EVIDENCE OF POLARIZATION EFFECTS IN DOPED $Al_(x)Ga_{1-x}N$/GaN SUPERLATTICES. Erik Waldron, E. Fred Schubert, John Graff, Boston University Photonics Center, Boston, MA; Andrei Osinsky, NZ Applied Technologies, Woburn, MA; Michael Murphy, William Schaff, School of Electrical Engineering, Cornell University, Ithaca, NY.

Room temperature and low temperature photoluminescence studies of Mg doped $Al_xGa_{1-x}N$/GaN superlattices reveal a red shift of the dominant transition band relative to the bulk GaN bandgap. The shift is attributed to the quantum-confined Stark effect resulting from polarization fields in the superlattices. A theoretical model for the band-to-band transition energies based on perturbation theory and a variational approach is developed. Comparison of the experimental data with this model yields a polarization field of 4.6×10^5 V/cm for room temperature $Al_{0.1}Ga_{0.9}N$/GaN and 4.5×10^5 V/cm for room temperature $Al_{0.2}Ga_{0.8}N$/GaN. At low temperatures the model yields 5.3×10^5 V/cm for $Al_{0.1}Ga_{0.9}N$/GaN and 6.3×10^5 V/cm for $Al_{0.2}Ga_{0.8}N$/GaN. The emission bands exhibit a blue shift at high excitation densities indicating screening of internal polarization fields by photo-generated free carriers.

G11.2
GROWTH AND INVESTIGATION OF GaN/AlN QUANTUM DOTS. H. Morkoc, M.A. Reshchikov, J. Cui, M.H. Zhang, F. Yun, M.I. Nathan, Virginia Commonwealth University, Richmond, VA; P. Visconti, Virginia Commonwealth University, Richmond, VA and Istituto per lo Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY; R. Molnar, MIT Lincoln Laboratories, Lexington, MA.

Quantum dots (QDs) in nitride based structures are expected to improve characteristics of the visible-to-UV optical emitters which are currently produced by employing two- and three-dimensional growth. We have fabricated GaN QDs in AlN confining layer structures by reactive and RF molecular beam epitaxy. The size distribution and density of the QDs have been estimated from the atomic force microscopy study. Very high quantum efficiency of photoluminescence (PL) has been obtained in the samples with QDs. Compared to the GaN bulk samples it increased by orders of magnitude. In some samples the quantum size effect dominated, resulting in the blue-shift of the QD related PL peak, whereas in the samples with larger dots red-shift up to 0.8 eV has been observed, which is related to strong polarization effects. We have observed a blue-shift of the PL peak with excitation intensity in most of samples studied. This phenomenon has been attributed to the screening effect in the dots with large lateral size. The temperature-induced quenching of PL begins at high temperature compared to the bulk GaN due to confinement of nonequilibrium carriers in the QDs. We have also carried out experiments with selective etching in the samples with quantum wells and dots, the results of which will also be discussed.

G11.3
ELECTRICAL PROPERTIES AND STRUCTURE OF Ni/Au CONTACTS ON P-TYPE GaN. Shi K. Chen, Shang C. Chiou, Jyh R. Gong, Feng Chia Univ, Dept of Materials Science, Taichung, REPUBLIC OF CHINA.

In this study, Ni/Au (5nm/5nm) was prepared by electron beam deposition to form the ohmic contact on p-type GaN with carrier concentrations of 2 Exp (17) per cubic centimeter. The as-deposited contact exhibited a specific contact resistance and transmittance of 0.39 ohm-cm^2 and 41%, respectively. However, after alloyed at 500 degree Centigrade for 10 minutes they became 0.020 ohm-cm^2 and 78%, respectively. The improvement in contact resistance and optical transmittance can be closely related to the interdiffusion in the metal/semiconductor interface and the formation of intermetallic phases Ga_4Ni_3 and Ga_2Au_7.

G11.4
AlGaInN QUARTERNARY CONDUCTING FILMS FOR SOLAR BLIND DETECTOR APPLICATIONS. Remis Gaska, Michael S. Shur, SET, Inc.; R. Srinavasan, G. Tamulaitis, V. Adivarahan, M. Asif Khan, J.W. Yang, Univ South Carolina, Dept ECE.

We report on the growth and characterization of solar blind Al 0.37Ga0.63-xInxN quarternary conducting films for solar blind photodetector applications. The films were grown by MOCVD on sapphire substrates. The addition of indium allows us to obtain crack-free films with good surface morphology and small surface roughness and achieve the dopant incorporation into the films. The Hall measurements yield the carrier concentration of 1017 cm-3 in the films with the Hall mobility of 6 cm2/Vs. The measured transmission spectra have a sharp cutoff at 281.5 nm corresponding to the band edge of 4.4 eV. These results confirm that incorporation of even minute amounts of indium greatly improves materials quality and should allow us to obtain conducting quarternary AlGaInN alloys with a much higher concentration of Al than what has been achieved for conducting ternary AlGaN compounds.

G11.5
ANISOTROPY OF INTERBAND MATRIX ELEMENTS IN WURTZITE GaN. A.V. Rodina, B.K. Meyer, I. Physics Institute, Justus Liebig University of Giessen, GERMANY.

We present the second order perturbation theory for the electron

effective mass and effective g-values tensors in hexagonal semiconductors with wurtzite symmetry using the five band **k·p** Kane model. The axial anisotropy of the interband Kane matrix elements is taken into account. The experimental data for the electron effective masses and effective g-values are used for the evaluation of four Kane matrix elements in wurtzite GaN. We found that anisotropy of the matrix element describing the interaction between the lowest and higher conduction bands is two times larger than the anisotropy of the matrix elements describing the interaction between conduction and valence bands. Taking into account the anisotropy of the interband matrix elements allows us to explain the experimentally observed sign of the electron effective g-factor anisotropy in GaN samples with different strain situation. We analyze the relative contributions of the valence band states, higher conduction band states and remote bands to the electron effective masses and g- values in wurtzite GaN and give a comparison with cubic semiconductors and other hexagonal semiconductors such as ZnO, CdS and CdSe. In contrast to the situation in cubic semiconductors [1], the higher conduction bands in wide band gap GaN give the major contribution to the electron effective g-factor tensor and its anisotropy. This can be explained by the relatively small value of the spin–orbit interaction in the valence band and the large value of the spin-orbit interaction in the higher conduction band of GaN. The electron effective mass in GaN can be described with an accuracy of about 60 - 80% within the three band **k·p** Kane model. [1] C. Hermann and C. Weisbuch, Phys. Rev. B **15**, 823 (1977).

G11.6
IMPACT OF THE GROWTH POLAR DIRECTION ON THE EMISSION MECHANISMS OF GaN FILMS GROWN BY METALORGANIC VAPOR PHASE EPITAXY. A. Setoguchi, A. Uedono, S. Chichibu, University of Tsukuba, Institute of Applied Physics, Tsukuba, JAPAN; K. Yoshimura, M. Sumiya, Shizuoka University, Department of Electrical and Electronic Engineering, Hamamatsu, JAPAN.

GaN and related alloys are attracting special attention since they serve as base materials for light emitting devices operating in UV to amber spectral region. Different from other III-V semiconductors like GaAs, GaN-based devices are fabricated on the c-plane sapphire substrates along the polar axis of the wurtzite structure. Polarity of GaN films have been identified by several groups. However, correlation between the growth polar direction and emission mechanisms of the grown film is still unclear at present. In this contribution, impact of the growth polar direction on the optical properties of GaN films during MOVPE on sapphire will be discussed in connection with impurity and vacancy incorporation. Optical absorption and photoluminescence spectra of GaN films grown toward different polar direction are compared. SIMS and monoenergetic slow positorn annihilation technique are used to analyze impurity and vacancy defect profiles. The GaN film grown toward the Ga (0001) face (c polarity) exhibited clear excitonic features in its optical absorption and luminescence spectra up to room temperature. Conversely, the film with the N (000 -1) face (-c polarity) exhibited a broad emission band, which locates in the broad absorption tail. The difference between the two is explained in terms of the presence of an impurity-induced band tail states in -c GaN due to increased imputiry density and enhanced incorporation of vacancy defects. The -c GaN contains large volume vacancy defects and donor impurities, which produce extended band tail states. Precise control of the growth polar direction is necessary to obtain low defect density materials as well as specular surface.

G11.7
STRUCTURAL EVOLUTION OF Ni/Au CONTACT ON GaN(000L). C.C. Kim, J.K. Kim, J.L. Lee, and J.H. Je, Department of Materials Science and Engineering, Pohang University of Science and Engineering, Pohang, KOREA; M.S. Yi, J.W. Kim, and D.Y. Noh, Department of Materials Science and Engineering and Center for Electronic Materials Research, Kwangju Institute of Science and Technology, Kwangju, KOREA; P. Ruterana, Equipe Structure et Comportement Thermomecanique des Materiaux (CRISMAT UMR 6508 CNRS), Caen, FRANCE.

While GaN has attracted considerable interests in high-temperature and high-power applications, the structural behavior of metal contacts at elevated temperatures has not been clearly understood yet. Ni/Au system was known as one of the most competing candidates in ohmic contact to p-type GaN as well as in Schottky barrier to n-type GaN. We investigated the structural behavior of Ni/Au contact system on GaN(000l) during annealing in N_2, using synchrotron x-ray scattering and high-resolution transmission electron microscopy. Ni/Au metal layers evaporated at room temperature were grown epitaxially on GaN(000l) with the relationship of M[111] // GaN[0001] and M[1-10] // GaN[11-20]; M=Ni, Au. As the annealing temperature increased up to 550°C, thermally activated atomic mobility caused metal atoms to diffuse into each other. At 700°C, extensive reactions were found to take place: Ga reacted preferentially with Au and nitrogen with Ni, forming Au-Ga solid solution and Ni_4N, respectively. The two phases were grown epitaxially with the same crystallographic orientations as the metal cubic structure. We attributed the drastic deterioration of the ohmic property at high temperatures to the formation of these phases.

G11.8
POLARITY of HEXAGONAL GaN GROWN ON GaAs (111)A AND (111)B SURFACES BY HVPE AND MOVPE. Osamu Takahashi, Makoto Namerikawa, Univ. of Tsukuba, Inst. of Applied Physics, Tsukuba, JAPAN; Hidenao Tanaka, NTT Cyber Space Laboratories, Musashino-shi, JAPAN; Ryutaro Souda, Nat. Inst. for Research in Inorganic Materials, Tsukuba, JAPAN; Takashi Suemasu and Fumio Hasegawa, Univ. of Tsukuba, Inst. of Applied Physics, Tsukuba, JAPAN.

Polarity of hexagonal GaN is an important parameter which influences crystal quality of epitaxial GaN. Since a (111) GaAs substrate has its own polarity, it is expected that GaN grown on (111) GaAs inherits the substrate polarity. HVPE growth on (111) GaAs is promising for obtaining a GaN substrate, so the polarity was investigated by CAICISS (Coaxial Impact Collision Ion Scattering Spectroscopy), and was compared with that for MOVPE GaN on (111) GaAs. GaN was grown by conventional HVPE and by low pressure MOVPE. For HVPE, about 100 nm GaN buffer layer was grown at 550°C with the V/III ratio of 200. Then about 3 um intermediate layer was grown at 850°C and finally about 30 um thick GaN was grown at 1000°C (V/III=50). For MOVPE, about 10 nm GaN buffer layer was grown at 570°C(V/III=1000) and about 500 nm GaN layer was grown at 950°C (V/III=30, 4800). HVPE buffer layer showed no structure in CAICISS spectrum, though the XRD spectrum indicated that the layer was well c-axis oriented. Both intermediate layers grown on (111)A and B surfaces at 850°C showed typical N-polarity CAICISS spectrum, even if the surfaces were rough. Thick GaN layers grown at 1000°C on (111)A and B showed almost the same CAICISS spectrum of N-polarity, though the grown surface was mirror like. On the contrary, MOVPE GaN grown on (111)B surface with the V/III ratio of 30 showed a typical Ga-polarity CAICISS spectrum, and the layer grown on (111)A with the V/III ratio of 4,800 did not show feature of the Ga-polarity spectrum. These results indicate that the polarity is greatly influenced by quality of the low temperature buffer layer and by the growth condition, especially by the V/III ratio, but not necessarily by the substrate polarity itself.

G11.9
CHARACTERIZATION OF HETERO-INTERFACES BETWEEN VARIOUS SUBSTRATES AND NITRIDE SEMICONDUCTORS GROWN BY LASER MBE. Jitsuo Ohta, Hiroshi Fujioka, Masaharu Oshima, The University of Tokyo, Department of Applied Chemistry, Tokyo, JAPAN; Masatomo Sumiya, Electrical and Electronic Engineering, Shizuoka University, Shizuoka, JAPAN; Mitsuyasu Furusawa, Mamoru Yoshimoto, Hideomi Koinuma, Materials and Structures Laboratory, Tokyo Institute of Technology, Kanagawa, JAPAN.

Epitaxial growths of group III-nitride semiconductors are usually carried out with MOCVD or plasma assisted MBE. Since these techniques involve highly reactive nitrogen sources such as ammonia or nitrogen plasma, it is believed that the surfaces of the substrates just before the epitaxial growths are nitrided. On the other hand, laser MBE offers a possibility for formation of abrupt hetero-interfaces between substrates and nitride semiconductors because active nitrogen species and group III atoms arrive on the substrates simultaneously. In this presentation, we will discuss the initial stage of hetero-epitaxial growths of nitride semiconductors by laser MBE on various substrates. We have grown GaN and AlN films on Si, sapphire, and LSAT substrates with a KrF excimer laser MBE apparatus. The laser light ablated the target with an energy density of 3 J/cm^2. During the film growth at a substrate temperature of 800°C, N_2 gas was introduced up to 1×10^{-5} torr for AlN and 5×10^{-5} torr for GaN. We investigated the hetero-interfaces with RHEED, AFM, XPS, and CAICISS. We have found that high quality nitride epitaxial films can be grown not only on Si and sapphire but also on LSAT using laser MBE. It should be noted that the crystalline quality of LSAT surfaces is easily degraded in MOCVD chambers by the exposure to ammonia, which causes poor crystallinity of nitride films deposited on the substrates. The RHEED observations of initial stages of the AlN epitaxial growths on these substrates have revealed that most growths start 2-dimensionally, followed by the 3-dimensional island formation. The Ga CAICISS spectra have shown that the polarity of GaN films are c, which provides striking contrast to the -c growths in conventional plasma assisted MBE.

G11.10
ELECTRICAL AND STRUCTURAL CHARACTERISTICS OF Ti, Pd AND Ni/N-$Al_{0.11}Ga_{0.89}N$ SCHOTTKY DIODES.

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Schottky diodes of Ti, Pd and Ni/n-$Al_{0.11}Ga_{0.89}N$ have been fabricated and the Schottky barrier heights were measured using I-V, I-V-T and C-V measurements. Fabricated diodes were annealed with different temperatures and time to understand the electrical and structural characteristics. Annealed Schottky diodes are showing higher I-V and C-V barrier heights when it compared with as-deposited Schottky diodes except high temperature annealed (450°C/30 min - 500°C/1 hr) Ti Schottky diodes. I-V barrier height of Ti/n-$Al_{0.11}Ga_{0.89}N$ increases up to the annealing temperature 350°C/5 min and it was decreases for higher annealing temperatures. C-V barrier height increases up to the annealing temperature 150°C/5 min for Ti (1.63 eV), 250°C/5 min for both Pd (1.68 eV) and Ni (1.54 eV) Schottky diodes respectively. The increase of barrier heights for low temperature annealing may not be any macroscopic interfacial reaction. Rectifying behaviour has been observed up to the annealing temperature 450°C/1 hr for Ni/n-$Al_{0.11}Ga_{0.89}N$ and 500°C/1 hr for both Ti and Pd/n-$Al_{0.11}Ga_{0.89}N$ Schottky diodes. Change of surface morphology has been observed using SEM and AFM in the annealed Schottky diodes. An increase of surface average roughness has been observed for the annealed Pd and Ni Schottky diodes except Ti Schottky diodes. Structural characteristics were carried out using XRD method to confirm the metal-semiconductor interfacial reactions. Structural and Electrical characteristics of the fabricated $Al_{0.11}Ga_{0.89}N$ Schottky diodes will be discussed in detail.

G11.11
AlGaN/InGaN HETEROSTRUCTURE FIELD EFFECT TRANSISTORS GROWN ON SAPPHIRE BY METAL-ORGANIC CHEMICAL VAPOR DEPOSITION. Jen-Inn Chyi, Chia-Min Kan, Tzer-En Nee, Chang-Cheng Chuo, Chia-Ming Lee, Department of Electrical Engineering, National Central University, Chung-Li, Taiwan, R.O. CHINA; Chin-Kun Peng, Procomp Informatics, Science-Based Industrial Park, Hsinchu, Taiwan, R.O. CHINA.

III-nitride materials have been recognized as a key player in high-temperature, high-power, and high-speed electronic devices. Most of the previous work has focused on AlGaN/GaN high electron mobility transistor. In order to improve the carrier confinement in the channel, an AlGaN/InGaN heterostructure field effect transistor is proposed and demonstrated. Its electrical, structural, optical and thermal properties are investigated in this work. The heterostructure was grown on a c-face sapphire substrate in a horizontal metal-organic chemical vapor deposition system. It consists of a 30 nm-thick low temperature (530°C) GaN nucleation layer, a 3 μm-thick high temperature (1050°C) GaN buffer layer, a 15 nm-thick $In_{0.08}Ga_{0.92}N$ channel layer, a 40 nm-thick $Al_{0.18}Ga_{0.82}N$ Schottky layer, and a 10 nm-thick GaN cap layer. The entire structure is undoped since spontaneous polarization induces the electrons for transistor operation. The InGaN channel gives an emission peak at about 395 nm in photoluminescence measurement. Transistors with gate length ranging from 0.8 to 4.0 μm were fabricated using Ti/Al/Ni/Au and Ni/Au as the ohmic and Schottky metal, respectively. The transistors exhibit good pinch-off characteristics with a threshold voltage of about -0.35 V and a saturation current density of 0.55 A/mm. At room temperature, a peak transconductance of 140 and 120 (mS/mm) was obtained for the 0.8 and 1.0 μm-device, respectively. As the temperature is increased to 300°C, the transconductance decreases to 50 mS/mm accompanied by a reduction of saturation current density of 0.24 A/mm due to the enhanced carrier scattering and gate leakage. Transmission electron microscopy shows that there are no dislocations induced by inserting the InGaN channel while a variation of strain field across the channel is observed. It is believed that higher performance can be achieved as the layer structure and growth parameters are optimized.

G11.12
THE NATURE OF CONDUCTIVITY IN HEAVILY BORON-DOPED DIAMOND. Rinat Mamin, Kazan Physical-Technical Inst. of RAS, Kazan, RUSSIA; Takashi Inushima, Dept. Communication Engineering, Tokai University, Hiratsuka, JAPAN.

The conductivity of boron-doped diamond is analyzed. To clarify the peculiarities of the transition from the band conductivity to the hopping one, we introduce a new idea connected with the appearance of the new states of the main impurity as the doping level increases. Two impurity atoms situated close to each other should have a new state with the energy different from the energy of impurity in a usual position. These states are ground states and in this sense differ from D^- states. It is shown that heavily doped diamond have the hopping shallow levels at $u_2 \approx 0.06eV$ above the valence band and lightly doped one had the activation energy of $u_1 = 0.37eV$. The density of the upper trap level is much smaller than that of the lower trap level. Small compensation has a significant role to explain the conduction of the diamond. On the basis of the Fermi level calculation the model for the conductivity of heavily boron-doped diamond is proposed. This model allows to reproduce the temperature dependence of the conductivity and of the Hall coefficient for different impurity concentrations. The temperature dependence of conductivity has been found to be connected with the co-existence of the valence-band and hopping conductivities in a wide temperature range. The hopping conductivity takes place over the new states of boron and can be assisted by the excited states of boron in the usual position or by D^- states. A scenario of the transition to the hopping conductivity for the heavily doped diamond is as follows. As the temperature decreases, first the band conductivity with the activation energy u_1 is observed, then a gradual transition to the state when only holes thermoactivated from the level u_2 participate in the valence-band conductivity takes place. At the same time, the hopping conductivity on the levels u_2 increases and at lower temperatures, when thermoactivation from the level u_2 weakens, it be comes dominating. In fact, the change of Fermi level with temperature can be interpreted as the observation of the activation energy ϵ_2. In our case the observation of ϵ_2 is due to the transition from the valence-band conductivity to the hopping conductivity on the level u_2 via the temperature change of the activation energy which follows the temperature change of the Fermi level. Thus ϵ_2 is a manifestation of the temperature change of the Fermi energy in a certain temperature range.

G11.13
EMISSION CHARACTERISTICS OF GaN-BASED EL DEVICE WITH AC OPERATION. Tohru Honda, Hideo Kawanishi, Kohgakuin Univ., Dept. of Electronic Engineering, Tokyo, JAPAN.

The GaN-based electroluminescence device (ELD) was fabricated using a GaN powder as an emission layer. The electroluminescence spectra of the GaN ELD under AC operation were observed at room temperature. The GaN layer was deposited using the GaN powder and methanol at room temperature after the synthesis of the its powder. The results indicate that the GaN-based ELD will be one of the suitable light-emitting devices for the flat display panels with low cost processes and wide area fabrications. The emission characteristics of GaN-based ELD were studied to compare the EL spectra and CL spectra. It is clarified that the emission spectra were similar to the CL spectra of a GaN emission layer. However, the emission peaks in the EL spectra was shifted toward high-energy side by increasing the frequency.

G11.14
HIGH-TEMPERATURE ELECTRON TRANSPORT PROPERTIES IN AlGaN/GaN HETEROSTRUCTURE FIELD EFFECT TRANSISTORS. Narihiko Maeda, Tadashi Saitoh, Kotaro Tsubaki, Toshio Nishida, Naoki Kobayashi, NTT Basic Research Laboratories, Physical Science Laboratory, Kanagawa, JAPAN.

The two-dimensional electron gas (2DEG) transport properties in AlGaN/GaN heterostructure field effect transistors (HFETs) have been examined from room temperature (R.T.) to 400°C. The temperature dependence of the 2DEG mobility has exhibited features of polar optical (PO) phonon limited mobility. Moreover, the 2DEG mobility above R.T. has been found to be relatively large even at high 2DEG densities beyond the channel capacity. The AlGaN (Al=0.15, Si-doped, 300 Å/GaN HFET samples, and Si-doped GaN and AlGaN (Al=0.15) single-layer samples, were grown on SiC substrates using AlN buffer layers by metalorganic vapor-phase epitaxy (MOVPE) at 300 Torr. As the typical mobility data, HFET with a high 2DEG density (1.7×10^{13} cm^{-2} at R.T.) exhibited mobilities of 720 and 110 cm^2/Vs at R.T. and 400°C, respectively; while bulk GaN ($2x10^{18}$ cm^{-3}) exhibited mobilities of 210 cm^2/Vs (R.T.) and 65 cm^2/Vs (400°C). Although the mobility rapidly decreases with increasing the temperature at around R.T., the decrease ratio in the mobility becomes small above 300°C. More rapid reduction in the mobility in HFET compared with that in bulk GaN has been observed, although the mobility in HFET has been kept higher than that in bulk GaN. This feature is ascribed to the strong 2DEG confinement in HFET with high electron densities in the order of 10^{19} cm^{-3}. Moreover, the decrease in the 2DEG mobility has been found to be relatively small even when the 2DEG density exceeds the intrinsic channel capacity (1×10^{13} cm^{-2}) and the parallel conduction occurs. This is due to the relatively high mobility in the bulk AlGaN (115 cm^2/Vs at R.T. for 1.3×10^{18} cm^{-3}). It should be noted that the observed feature presents a possibility for utilizing high electron densities that exceed the channel capacity, especially in the case of high-temperature device applications.

G11.15
LOW RESISTANCE AND THERMALLY STABLE OHMIC CONTACTS TO P-TYPE GaN. Ja-Soon Jang, Sang-Heon Han, Dong-Jun Kim, Seong-Ju Park and Tae-Yeon Seong, Kwangju

Institute of Science and Technology (K-JIST), Dept of MS&E, Kwangju, KOREA.

We investigate the electrical and thermal stability of Pt-based Ohmic contacts to P-GaN:Mg (N_a = ~3x10^{17} cm^{-3}), which was two-step surface-treated using buffered oxide etch (BOE) and ammonium sulfide [$(NH_4)_2S_x$] solutions. The Pt (20 nm), Pt/Ru (20 nm/50 nm), and Pt/Ru/Au (20 nm/20 nm/50 nm) films were deposited on the surface-treated p-GaN by electron beam evaporation. Some of the contacts were rapid-thermal-annealed in N2 ambient. The current-voltage (I-V) measurements show that the as-deposited contacts produce a specific contact resistance in the range of 7.1x10^{-4} - 5.9x10^{-4} Ω cm^2. However, annealing of the contacts at 600°C results in a contact resistance in the range of 4.8x10^{-4} - 1.4x10^{-6} Ω cm^2. It should be stressed that for the Pt/Ru-based contacts, the annealing results in a drastic reduction in the specific contact resistance by more than two orders of magnitude, compared to the as-deposited contacts. The light transmittance characteristics of the contacts are also investigated in terms of film thickness and treatment conditions. Measurements show that the transmittance is in the range of 87 - 93% at 430 - 470 nm. Post-deposition annealing treatment is performed to investigate the thermal stability of the surface-treated contacts. To understand Ohmic mechanisms for the Pt-based contacts, electronic transport mechanisms and interfacial reactions are investigated using X-ray photoelectron spectroscopy, I-V-T measurement, Auger electron spectroscopy, Glancing X-ray diffraction, and transmission electron microscopy.

G11.16
THE IMPROVEMENTS IN THE ELECTRICAL AND OPTICAL PERFORMANCE OF InGaN/GaN MULTI QUANTUM WELL LIGHT EMITTING DIODES BY TWO-STEP SURFACE-TREATMENT. J.-S. Jang, H.-S. Kim, S.-W. Kim, J.-M. Lee, S.-J. Park, H. Hwang, and T.-Y. Seong, Dept of Materials Science and Engineering, Kwangju Inst of Science and Technology, (K-JIST), Kwangju, KOREA; K.-S. Kim and G.-M. Yang, Semiconductor Physics Research Center, Chonbuk National Univ, Chonju, Chonbuk, KOREA.

We investigate the effects of two-step surface-treatment on the electrical and optical device performance of InGaN/GaN MQW LEDs using current-voltage (I-V) and electroluminescence (EL) measurements. The InGaN/GaN MQW layers were grown on Si-doped GaN/(0001) sapphire substrates using MOCVD. This was followed by the growth of p-type GaN:Mg layers. The surface-treatment was performed after mesa patterning (first step) and before metal deposition (second step) using buffered oxide etch (BOE) solution. Pt/Ru and Ti/Au metallization schemes were used as p- and n-ohmic electrodes, respectively. Performance of the two-step treated LEDs is compared with that of the conventionally treated LEDs. The I-V measurement shows that the forward voltage of the two-step treated LEDs is lower than that of conventionally treated LEDs by ~1 V at a measuring current of 20 mA. It is also shown that the optical output power of the two-step treated LEDs improves significantly, compared to that of the conventionally treated LEDs. EL measurement shows that the maximum peak is observed at 436 nm for both LEDs. It is further shown that the EL intensity of the two-step treated LEDs becomes stronger than that of the conventionally treated LEDs. For the two-step treated LEDs, the EL intensity is uniform across the whole Pt/Ru transparency layer, while for the conventionally treated ones, randomly distributed dark spots are observed. The surface treatment dependence of the uniformity of EL intensity is discussed in terms of surface state density and the alignment of metal grains. Interface characteristics are investigated using X-ray photoelectron spectroscopy and time resolved EL measurement to investigate the effects of contact stability on the performance of LEDs.

G11.17
CHARACTERIZATION OF GaN THIN FILMS GROWN BY RF-PLASMA ENHANCED MBE ON HVPE GaN TEMPLATES. W.K. Fong, C.F. Zhu, B.H. Leung, C.C. Cheng, C. Surya, The Hong Kong Polytechnic Univ, Dept of Electronic and Information Engineering, Hong Kong, CHINA; B. Sundaravel, E.Z. Luo, J.B. Xu, I.H. Wilson, The Chinese Univ of Hong Kong, Dept of Electronic Engineering and Materials Technology Research Center, Hong Kong, CHINA.

Gallium nitride films were grown by rf-plasma assisted molecular beam epitaxy (MBE) on hydride vapor phase epitaxy (HVPE) GaN templates. The optical and structural properties of the films were characterized by investigating the photoluminescence (PL), high resolution x-ray diffraction (HRXRD), and Rutherford Backscattering Spectroscopy (RBS). It is observed that GaN films grown by MBE on HVPE GaN templates exhibited significant enhancement in bandedge transition at 3.4 eV comparing to the original HVPE GaN templates. No detectable yellow luminescence (YL) is found on the MBE grown GaN and YL is observed in HVPE GaN templates. Significant reduction in the full width at half maximum of the GaN (0002) rocking curve indicated that a better structural quality was obtained when GaN films were grown on HVPE GaN templates. RBS and ion channeling measurements also revealed a better film quality can be obtained when using HVPE grown GaN as a template.

G11.18
ELECTRICAL PROPERTY OF InN GROWN BY RF-MBE. Yoshiki Saito, Tomohiro Yamaguchi, Tsutomu Araki, Yasushi Nanishi, Ritsumeikan Univ, Dept of Photonics, Shiga, JAPAN; Nobuaki Teraguchi, Akira Suzuki, Sharp Corp, Advanced Tech. Res. Labs., Nara, JAPAN.

InN has smaller effective mass and higher electron drift velocity than those of GaN. Therefore, InN is expected to be promising for the future electronic devices. InN, however, tends to grow three-dimensionally because of the lattice mismatch is large between the InN films and the substrates. In this paper, we demonstrate a successful growth of InN films with excellent surface morphology and electrical property by growing at 550°C on the buffer layer prepared by low temperature growth and consecutive annealing. InN films were grown by RF-MBE. The substrate used in this study was (0001) sapphire. Prior to growth of InN, thermal cleaning of the sapphire substrate was carried out at 800°C for 10 min to obtain a clean surface. Then, nitridation was carried out at 550°C for 1 hour with nitrogen flow rate of 1 sccm and RF plasma power of 300 W. Following the nitridation process, InN buffer layers were grown at 300°C for 10 min. Then, the substrate temperature was raised up to 550°C, then InN films were grown again on the buffer layers thus prepared at 550°C for 1 hour. The beam equivalent pressure of the elemental In and the N_2 flow rate were 3.2x10^{-7} Torr and 2 sccm, respectively and kept constant through out the experiment. Only RF power was varied between 230 W and 250 W. Thickness of the InN film grown for 1 hour was about 200 nm. From SEM observation, it was found that surface morphology was improved by reducing RF power to 230 W. Many In droplets were appeared, however, on the surface of InN film. From Hall measurements, the InN film grown at 230 W was confirmed to have excellent electrical property with its electron mobility of 756 cm^2/Vs at room temperature and carrier density of 3.0x10^{19} cm^{-3}.

G11.19
500 nm InGaN/GaN SQW INDUCED BY PIEZOELECTRIC FIELD EFFECT AND PHASE SEPARATION. Bong Kee, Euijoog Yoon, Seoul National University, School of Materials Science and Engineering, Seoul, KOREA; Jongman Koh, Samsung Electro-Mechanics, Co., Ltd., Suwon, KOREA.

Despite rapid advances in growth technology, the high-indium, high-quality InGaN films are still difficult to grow. Recombination of electron-hole pairs in InGaN/GaN quantum well structures is affected by two factors. First, strong piezoelectric field cross the InGaN/GaN quantum well tends to separate electrons and holes in the quantum well, leading to a strong red-shift of resonance energy and reduced oscillator strength. Second, recombination of localized excitons due to compositional fluctuation or phase separation must be taken into account. Especially, phase separation can be very useful to obtain high-efficiency, high-In content InGaN layers.[1,2,3] In this work we grew two InGaN/GaN single quantum well samples with the same emission wavelength of 500 nm by MOCVD by two different approaches. The first 500 nm sample (Sample A) was obtained by increasing the piezoelectric field with increased well width of 3.5 nm. The second 500 nm sample (Sample B) was phase-separated by adjusting the V/III ratio during the growth. In this samples, the quantum well thickness was 3.0 nm. Temperature dependent and excitation power dependent photoluminescence measurement was performed for these samples. Sample A showed slight red shift as temperature increased and excitation power decreased. On the other hand, sample B showed profound band tail broadening as temperature increased and excitation power decreased, strongly suggesting that localized states exist in the phase-separated InGaN layers. The electroluminescence image of the phase-separated InGaN/GaN quantum well structure was obtained by optical microscopy at low current injection. High-brightness spots with longer wavelength in the sample B clearly demonstrate that high-efficiency, longer wavelength InGaN/GaN quantum well structures can be obtained by phase separation. [1] C.A. Tran, R. Stall, J. Crystal Growth 195 397 (1998). [2] M. Pophristic, and C.A. Tran, Appl. Phys. Lett. 73, 815 (1998). [3] M. Pophristic and C.A. Tran, J. Appl. Phys. 86, 1114 (1999)

G11.20
MAPPING OF POLARIZATION FIELDS AND FREE CARRIER SCREENING EFFECTS IN GaN/InGaN/GaN SINGLE QUANTUM WELL STRUCTURES BY ELECTRON HOLOGRAPHY. Juan Cai, M.R. McCartney, and F.A. Ponce, Department of Physics and Center for Solid State Science, Arizona State University, Tempe, AZ.

The determination of the internal electric field due to spontaneous

polarization and piezoelectric effects in strained heterostructures of the group III wurtzite nitrides is critical for understanding the optical transitions in optoelectronic devices. Electron holography provides us with the ability to profile the local internal potential at the angstrom level using the interference between a reference wave and a wave traversing through the sample. In this study, we have used electron holography to characterize the electrostatic potential across the GaN / InGaN (27 Å) / GaN single quantum well (QW) structure. The hologram was taken with a sampling of 1 Å/pixel in the region. The slope of the potential profile shows that an internal electric field as large as 2.0 MV/cm exists in the InGaN QW. High-resolution electron hologram also reveals band bending over atomic spacing distance in the vicinity of two interfaces between GaN and InGaN. Simulations suggest that free electrons and holes with a concentration of $10^{20}/cm^3$ are confined in the region outside the InGaN QW interfaces. These free-carriers may screen part of the internal polarization field in the QW. The relationship between the holographic phase and the internal fields due to spontaneous and piezolelectric polarization and free and fixed charges associated with the interfaces will be discussed. These results allow us to accurately model the quantum well band structure and its relationship with interband light emission.

G11.21
INVESTIGATION OF SIDEWALL RECOMBINATION IN GALLIUM NITRIDE USING A QUANTUM WELL PROBE.
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As GaN material and device technology matures, there is growing interest in scaling devices to smaller dimensions. In doing so, it is important to consider the effects of air/semiconductor interfaces on device performance. Depending on the nature of the surface states and bond reconstruction, the air/semiconductor interface can be a source of nonradiative recombination. As the surface area to volume ratio increases, as in smaller optical devices, nonradiative sidewall recombination can become an increasingly dominant mechanism of recombination. Studies on GaAs- and InP-based materials have shown that sidewall recombination limits the scaling of lasers (in-plane and VCSELs) to a few microns and thus necessitates either regrowth or surface passivation. Scaling effects have yet to be fully characterized in GaN. In this study, we use a quantum well (QW) probe structure to explore the size dependent effects of sidewall recombination in GaN. The structure had an $In_{0.13}GaN$ QW capped with 150 Å GaN. Ridges of widths of approximately 2, 3, and 4 microns with fill factors of approximately 50% were etched into the QW structure. The ridges were formed using 500 eV Ar^+ ions with a beam current density of 0.200 mA/cm^2 for 15 minutes. Two different Cl_2 flows were used for these experiments: 0 sccm and 5 sccm. Depending on the Cl_2 flow, the etch depth was approximately 1500-3200 Å, therefore the 150 Å deep QW was exposed on the ridge sidewall. Room temperature PL measurements, using a He-Cd laser as an excitation source and laser spot size of approximately 400 microns, were taken before and after the ridges were etched. The effect of the sidewall etch was quantified by comparing the maximum PL intensity before and after etch. The fraction of remaining PL decreases with decreasing ridge width. These results show that even with 4 micron ridge width, sidewall recombination may indeed play a significant role in nonradiative recombination processes. Time-resolved photoluminescence (TRPL) carrier lifetime measurements are being taken to confirm this conclusion.

G11.22
HIGH MOBILITY TWO-DIMENSIONAL ELECTRON GASES IN AlGaN/GaN HETEROSTRUCTURES ON FREE-STANDING GaN QUASI-SUBSTRATES.
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Free-standing GaN quasi-substrates produced by laser lift-off of thick HVPE GaN-layers from sapphire are used to obtain high quality two-dimensional electron gases by homoepitaxial overgrowth with MBE and MOCVD. Homoepitaxial GaN-layers on such quasi-substrates exhibit a much lower dislocation density (2 x 10^7 cm^{-2}) and much lower thermal strain compared to heteroepitaxial GaN-layers e.g. grown on sapphire. Step-flow growth can readily be achieved by overgrowth with MOCVD, resulting in homoepitaxial layers with an rms surface roughness as low as 0.2 nm, X-ray diffraction patterns with a FWHM below 20 arcsec, and excitonic luninescence linewidths below 500 μeV. Two-dimensional electron gases are readily produced by depositing e.g. an AlGaN-heterolayer onto a GaN-substrate. The difference in the spontaneous pyroelectric polarization on each side of the heterostructure together with the piezoelectric polarization due to the residual strain give rise to a significant bound interface charge. This, in turn causes the appearance of a compensating 2-D electron gas with high carrier densities and interesting applications for high-frequency, high-power devices. In the present contribution, homoepitaxial AlGaN/GaN-heterojunctions deposited by MBE and MOCVD will be characterized with respect to their structural and electronic properties. Particular attention is paid to the correlation between structural and electrical characteristics of the samples. In addition, we have noticed a pronounced correlation between the size of van der Pauw or Hall bar contact geometries and the maximum observed mobility. This suggests that lateral inhomogeneties have a pronounced effect on the electronic properties of III-nitrides.

G11.23
THE ACOUSTIC PROPERTIES OF Mg-DOPED GALLIUM NITRIDE THIN FILMS OBTAINED BY SURFACE ACOUSTIC WAVE MEASUREMENTS.
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Gallium nitride and its solid solution with InN and AlN have attracted attention because of their potential optoelectonic applications as well as high-power and high-temperature electronic applications. For these applications, it is very important to prepare p-type GaN thin films, but doping GaN with acceptors to obtain a high concentration of holes has been a difficult problem. The emphasis has been on producing the films for the device developments, while little attention has been paid to the acoustic properties of the films. Since the film properties differ from bulk properties, it is necessary to acoustically characterize the films on the underlying substrates. In this study, gallium nitride and Mg-doped gallium nitride thin films were prepared on c-plane sapphire substrate by MOCVD. The Mg-doped GaN layers were deposited on GaN buffer layers. The GaN film properties were investigated using SEM, TEM, and high resolution XRD. To investigate the acoustic properties of the films, SAW filters were fabricated using interdigital transducer electrodes on the top of GaN/sapphire, which were used to excite surface acoustic waves. SAW velocities were calculated from the frequency-response measurements by using a network analyzer (HP8753D) test set with time gating at an input power level of 0 dBm. To interpret the measured dispersive SAW velocities, theoretical SAW velocities were simulated using numerical computations. We also calculated the film elastic constants from SAW propagation velocities in the layered structure. From the acoustic characterization, Mg-doped GaN thin films showed the stiffening effects and two elastic constants and propagation loss are similar to those obtained for pure GaN thin films.

G11.24
HIGH-FREQUENCY CAPACITANCE-VOLTAGE CHARACTERISTICS OF PECVD GROWN SiO_2 MIS STRUCTURE ON GaN AND GaN/$Al_{0.4}Ga_{0.6}$N/GaN HETEROSTRUCTURE.
P. Chen, Y.G. Zhou, H.M. Bu, W.P. Li, Z.Z. Chen, B. Shen, R. Zhang and Y.D. Zheng Department of Physics, Nanjing University, Nanjing, PR CHINA.

Excellent physical properties of GaN have attracted much attention for electronic device developments. Up to now, a number of GaN-based field-effect transistors (FETs) have been reported. For many applications, metal-insulator-semiconductor (MIS) technology is desirable since it would provide high DC input impedance, large gate voltage swings, normally-off operation with high source-drain blocking voltage, and high temperature operation as a result of reduced gate leakage. We have demonstrated an enhancement mode GaN-based MISFET on a GaN/AlGaN/GaN double heterojunction with SiO2 as gate insulator. However, there is a little known about the properties of such MIS structures now. It is important to investigate the high-frequency capacitance-voltage (C-V) characteristics under different measurement conditions for the different structures. MIS structures were fabricated by depositing SiO2 films at 310? on n-type GaN epitaxial layers and GaN/Al0.4Ga0.6N/GaN double heterojunction, which were grown by low-pressure metalorganic chemical vapor deposition on sapphire substrates. The SiO2 films were grown by plasma-enchanced chemical vapor deposition. The C-V characteristics were measured under normal condition, slow bias sweep and persistent negative bias. Under a bias between ±25 V, the agreement of the measured C-V curve of SiO2/n-GaN with the ideal curve in deep depletion and the very small hysteresis indicate that the interface traps concentration in the sample is low. The measured C-V curve gives an interface state density of 2.1- 1011 eV-1cm-2. However, for SiO2/GaN/Al0.4Ga0.6N/GaN, the measured C-V curves are very difference from the previous ones. A notable flat-band shift of about 15 V indicates the presence of position polarization charges in this structure. The capacitance on SiO2/GaN/Al0.4Ga0.6N/GaN can reach a minimum value under about -5V bias. The saturation at a minimum value of the C-V curve concludes the presence of a p-channel in the MIS structure. These results imply that the

piezoelectric effect in GaN/Al0.4Ga0.6N/GaN play an important role for the presence of the p-channel.

G11.25
ELECTRONIC STRUCTURE OF GaN QUANTUM DOTS WITH AN ADJACENT THREADING DISLOCATIONS. A.D. Andreev[1,2], J.R. Downes[2], E.P. O'Reilly[3]; [1]A.F. Ioffe Institute, St.-Petersburg, RUSSIA; [2]Physics Department, Queen Mary and Westfield Colledge, London, UNITED KINGDOM; [3]Physics Department, University of Surrey, Guildford, UNITED KINGDOM.

In this paper we present a theory of the electronic structure of GaN quantum dots with an adjacent threading dislocations. The QD carrier spectra and wave functions are calculated using a plane-wave expansion method we have developed, and a multi-band $\mathbf{k}\cdot\mathbf{P}$ model. The method used is very efficient, because the strain and built-in electric fields can be included analytically in full degree through their Fourier transforms. The QD structures considered for our theoretical analysis are those studied experimentally in [1] and [2]. The GaN QDs have the shape of truncated hexagonal pyramid sitting on the wetting layer with edge adjacent dislocation. The dominant effect is the built-in electric field potential which pushes the electrons to the top of the dot and the holes to the dot bottom and causes strong additional lateral confinement of the carries. As a result, the effective lateral dot size becomes smaller than the real dot size, the electron and hole are localised apart from the dislocation line. Therefore the effect of the dislocation strain field at the dot edge on the carrier states in GaN/AlN QD is minimal. Results are presented for energies and optical matrix elements for a range of differently sized dots with and without dislocations. The size of the dot influences the energies and overlaps, but the presence of the dislocation has no effect. The dependence of the ground state optical transition energy on the QD size is found in good agreement with experimental data of ref [1]. [1] F. Widmann, J. Simon, D. Daudin, G. Feuillet, J.L. Rouviere, N.T. Pelekanos, G. Fishman, Phys. Rev. B **58**, 15989 (1998) [2] J. L. Rouviére, J. Simon, N. Pelekanos, B. Daudin and G. Feuillet, Appl. Phys. Lett. **75**, 2632 (1999).

G11.26
NON-STATIONARY PHOTOCONDUCTIVITY OF GaN CLUSTERS EMBEDDED IN ARTIFICIAL OPAL MATRIX. M. Niehus, S. Koynov, R. Schwarz, Instituto Superior Tecnico, Departamento de Fisica, Lisboa, PORTUGAL; N.A. Feoktistov, V.G. Golubev, D.A. Kurdyukov, A.B. Pevtsov, Ioffe Institute, RAS, St. Petersburg, RUSSIA.

It was recently proposed to use synthetic opals as matrices (hosts) for obtaining 3D arrays of electronic nanodevices [1]. In the present work the opal matrices were infiltrated with GaN. This will enable to reach a working area of the junctions per unit volume in III nitride-based light emitting diodes (LEDs) as high as 10 m^2/cm^3 and to reduce the current density by 3-4 orders of magnitude as compared with conventional planar systems. To introduce GaN into the opal matrices we used heterogeneous chemical reactions of NH_3 with solid precursors containing Ga that were previously embedded inside the opal voids. XRD, AFM, and Raman measurements were carried out to determine the structural properties of opal-GaN composites. Non-stationary photoconductivity (PC) was studied with Q-switched Nd-YAG laser radiation. 5 ns pulses of 532 nm and 266 nm laser lines with energies of ca. 1 mJ yielded secondary photocurrents with photo-to-dark conductivity ratios of ca. 1000 (dark current was $2*10^{-7}$A with U_{bias}=30V). The PC peak values are proportional to the square-root of pulse energy, what usually occurs in insulators with bimolecular recombination. The initial photocurrent decay time was near to our detection limit of 25 ns. The long time non-exponential photocurrent decay lasts up to several hours and is usually referred to as persistent photoconductivity (PPC). The current build-up during pumping with the 532 nm laser line is characterized by a fast, superlinear increase, followed by a subsequent linear enhancement regime. The decay after pumping shows three distinct regions: a very fast decay to 50% during the first 10-20 s, followed by a power- law dominated decay with an initial exponent of 0.3, changing to an index of 1 at 1000 s. Our discussion will relate the above findings with similar effects usually found in bulk GaN material prepared by different methods, including the possible additional contribution of surface-related structural defects of the opal-GaN composites. This work was supported by the INCO-COPERNICUS program under grant no. IC15 CT98 0819. [1] V.N. Bogomolov, T.M. Pavlova. Semiconductors 29, 826 (1995).

G11.27
LOW-DARK-CURRENT SCHOTTKY BARRIER (Al)GaN UV DETECTORS. P.W. Deelman, R.N. Bicknell-Tassius, Jet Propulsion Laboratory, Pasadena, CA; S.A. Nikishin, H. Temkin, Dept of Electrical Engineering, Texas Tech Univ, Lubbock, TX.

We report mesa-isolated Schottky barrier photodetectors fabricated on *n*-(Al)GaN. Single-element detectors and 32 × 32 arrays were constructed from nitride epilayers grown by gas source molecular beam epitaxy on Si(111). Chlorine-based reactive ion etching was used to form two-level mesas. The detectors were front-illuminated through 100 Å Pd semitransparent Schottky contacts on the upper mesas; ohmic contact on the lower mesas was made using standard Ti/Al/Ti/Au metallurgy. Silicon dioxide grown by plasma-enhanced chemical vapor deposition provided both surface passivation and electrical isolation. The dark current of an $86 \times 86 \mu m^2$ single-element detector is $\sim 2.10 \times 10^{-8}$ A/cm^2 at -2 V bias. Results of noise measurements and performance will also be presented.

G11.28
AlN SAW SENSORS USING EXCIMER LASER MICRO-MACHINING TECHNIQUES. Feng Zhong, Qiang Zhao, Changhe Huang and Gregory W. Auner, Department of Electrical and Computer Engineering, Wayne State University, Detroit, MI.

AlN is a promising piezoelectric material for Surface Acoustic Wave (SAW) sensor application due to its high SAW velocity and electromechanical coupling coefficient. Epitaxial AlN thin films were successfully grown on the Sapphire and SiC substrates by Plasma Source Molecular Beam Epitaxy (PSMBE). The thin films were characterized as to their microstructure, surface morphology and acoustic properties. Standard SAW sensors were fabricated and characterized. The sensors suffer from excess attenuation when exposed to sensing environment, especially in liquid. Excimer laser micromachining techniques were utilized to fabricate microgrooves or microchannels on the surface of AlN SAW sensors to reduce the excess attenuation and improve the output signal. The effects of those micromachined channels on the performance of AlN SAW sensors will be presented.

G11.29
NATURE OF HIGHLY CONDUCTING INTERFACIAL LAYER IN HVPE GROWN GaN FILMS. Julia W.P. Hsu, D.V. Lang, S. Richter, R.N. Kleiman and A.M. Sergent, Bell Labs, Lucent Technologies, Murray Hill, NJ; R.J. Molnar, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, MA.

Using several derivatives of scanning force microscopy with conducting tips, we show direct evidence for the highly conducting interfacial region of GaN films grown on (0001) sapphire substrates by hydride vapor phase epitaxy (HVPE). HVPE films are used as templates for molecular beam epitaxial growth of GaN devices. Since this highly conducting layer co-exists with the rest of the GaN film and affects carrier transport at all temperatures, a better understanding of its nature and origin is needed. Hall measurements show that the carrier density increases and mobility decreases as temperature decreases. It has been proposed that GaN near the sapphire substrate is degenerate with a high electron density and low mobility. In this work, we perform several scanning probe microscopy measurements on the cross sections of GaN films to directly probe the electronic properties at the GaN-sapphire interface. Scanning current-voltage and capacitance microscopy measurements both show that the free electron density is much higher in the region of 0.1 to 0.3 μm from the GaN-sapphire interface. However, surface contact potential images reveal that the Fermi level in the interfacial region is 50 to 100 meV deeper into the bandgap than it is in the less conducting bulk film. These results are inconsistent with a high density of electrons in the intrinsic conduction band. Rather, they point to the existence of a partially filled donor impurity band with the Fermi level in the impurity band. A high concentration of oxygen and the defective microstructure at the GaN-sapphire interface are believed to be the origin of this anomalous conduction behavior. Submicron resolution offered by SPMs is critical for probing the effect of defects/impurities on materials physical properties.

G11.30
A HIGH RESISTIVITY GaN FORMED BY ION IMPLANTATION. Jun Kudo, Motonobu Yukawa, Yuji Hishida, and Masanori Watanabe, Ion Engineering Research Institute Corporation, Osaka, JAPAN.

The present paper describes the preparation of high resistivity GaN by ion implantation, which provides an effective means of electrical isolation in GaN microwave devices. Ar^+, C^+, N^+ or Zn^+ ions were implanted to a Si-doped epitaxial GaN layer, with 4×10^{18} cm^{-3} donor concentration and 0.6 μm thick, grown on the undoped GaN/AlN/sapphire substrate. A flat doping profile in the range of 10^{18} - $10^{20}cm^{-3}$ was obtained to the depth of 0.2 - 0.3 μm from the surface by multi-step implantation. After forming Ti/Al/Ni electrodes, the sample was annealed at 550 - 850°C for 1 min. The resistivity of as-implanted layer was 10^9 Ω·cm or larger, irrespective of the dopant species. However, it tended to decrease as a result of annealing at high temperature. For the implant dose of 10^{19}, while the resistivity of Ar^+-implanted layer rapidly decreased to 10^4 Ω·cm after annealing at 850°C, those of C^+- and N^+-implanted layers remained in 10^6 - 10^8 Ω·cm range after annealing at 800°C and 850°C,

respectively. For the same dose, the resistivity of Zn^+-implanted GaN layer decreased to 10^6 Ω·cm after annealing at 850°C, which is contrasted to the recent report by Kuznetsov et al. that GaN formed at 950 - 1050°C by hydride VPE, with Zn concentration of $2 \times 10^{18} cm^{-3}$, yielded the resistivity larger than 10^{10} Ω·cm. The present result has shown that the implantation of Ar^+, C^+, N^+ or Zn^+ ions yields a high resistivity GaN layer, which sustains high process temperatures, 700°C for Ar^+-implantation and even higher for C^+-, N^+-, and Zn^+-implantation. The resistivity of the implanted layer after annealing is apparently affected by two competing effects, namely, the recovery of implantation-induced defects, and the compensation of Si donors by electrically activated, implanted species.

G11.31
ELECTRIC FIELDS AND INTERDIFFUSION IN MOCVD GROWN GaN/AlGaN HETEROSTRUCTURES. M. Moret, S. Ruffenach-Clur, O. Briot, N. Moreaud, J. Calas, R.L. Aulombard, GES, Univ Montpellier II, Montpellier, FRANCE; J.L. Rouviere, CEA-CENG, Grenoble, FRANCE.

AlGaN/GaN heterostructures have both a theoretical and practical interest: due to their symetry, GaN and AlGaN crystals exhibit both spontaneous and piezoelectric polarization. This results in strong electric fields in their heterostructures, which can be used to induce 2D electron gas in HEMT transistors. Such high electric fields have been previously demonstrated in quantum wells, where they induce a quantum stark effect shift on the excitonic transitions, as observed in low temperature photoluminescence. From the analysis of published data, it appears that the strongest electric fields appear in MBE grown samples, while MOCVD grown samples exhibits lower electric fields. Since the electric field may be related to the gradient of polarization across the interface, one may think that MOCVD samples, grown at a high temperature suffer from a large inter-diffusion at the interfaces, thus smoothing the polarization profile at the interface. We have grown GaN/AlGaN quantum wells by low pressure MOCVD at high temperature (1140°C), with well thicknesses ranging from 5 to 25 monolayers and an Al composition of 13%. The samples were studied by low temperature (2K) photoluminescence and reflectivity, X-ray reciprocal space mapping, and transmission electron microscopy. Narrow PL lines are observed for the quantum wells, stokes-shifted from the reflectivity structures, and their energy positions versus well thickness clearly demonstrate the occurrence of quantum stark effect. The electric fields in the samples were deduced from the optical measurements using a self-consistent envelope function calculation. For thick quantum wells, the reflectivity structures are not directly observed and the localization energies are deduced from temperature dependent photoluminescence measurements, allowing a correct evaluation of the position of the fundamental well transition. The electric fields which were deduced are significantly lower than those observed in similar MBE samples. The well thicknesses and interface profiles were determined by transmission electron microscopy. Even at this very high growth temperature, no substantial interdiffusion explaining the reduction of the electric fields is observed.

G11.32
SELF-ALIGNED PROCESS FOR GaN/AlGaN HBTs. K.P. Lee, Univ of Florida, Dept of Materials Science and Engineering, Gainesville, FL; A.P. Zhang, F. Ren, Univ of Florida, Dept of Chemical Engineering, Gainesville, FL; J. Han, Sandia National Labs, Albuquerque, NM; W.S. Hobson, J. Lopata, AT&T Bell Labs, Lucent Technologies, Murray Hill, NJ; C.R. Abernathy, S.J. Pearton, Univ of Florida, Dept of Materials Science and Engineering, Gainesville, FL; J.W. Lee, Plasma Therm, St. Petersburg, FL.

We have developed a self-aligned fabrication process for small emitter contact area ($2x4\mu m^2$) GaN/AlGaN heterojunction bipolar transistors is descried. The fabrication empolys dielectric-spacer sidewalls, ICP dry etching and selected-area regrowth of GaAs(C) on the base contact. The junction I-V characteristics were evaluated at various stages of the process sequence and provided an excellent diagnostic for monitoring the effect of plasma processes such as CVD, for side wall formation or etching. A comparison will be given with the dc performance of large emitter-area ($2.5x104\mu m^2$) devices fabricated on the same material, allowing us to determine the effectiveness of scaling in the GaN system. The small-area HBTs are attractive for microwave power switching applications at elevated temperatures (≥300°C).

G11.33
HOT ELECTRON TRANSPORT IN AlN. Ramon Collazo, Raoul Schlesser, Amy Roskowski, Robert F. Davis, Zlatko Sitar, Dept of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

The energy distribution of electrons that were transported through a thin intrinsic AlN film was directly measured as a function of the applied field. The measurements were realized by extracting the electrons into vacuum through a semitransparent Au contact and measuring their energies using an electron spectrometer. At moderate applied fields (100 kV/cm), the energy distribution was found to follow a Maxwellian model corresponding to a temperature of 2700 K and a drift component below the spectrometer resolution. At higher fields, intervalley scattering was evidenced by the presence of a second peak at 0.7 eV. This coincides well with the energy position of the L-M valleys in AlN. To the best of our knowledge, these are the first measurements that offer direct evidence of intervalley scattering in any solid system.

G11.34
ELECTRIC FIELDS AT THE SiC/AlN AND SiC/GaN POLAR INTERFACES. Morad Rouhani Laridjani, Pierre Masri, Groupe d'Etude des Semiconducteurs, CNRS, UMR 5650, University of Montpellier, Montpellier, FRANCE; Jacek A. Majewski, Walter Schottky Institute, Technical University of Munich, Munich, GERMANY.

Growth of nitride films on hexagonal crystallographic phases of SiC along the hexagonal [0001] direction yields polar interfaces. There are two origins of the interface polarity. At abrupt interfaces, the group IV elements (Si and C) bind across the interface with group III or V elements. This gives undersatured or oversaturated bonds at the interface and as a result the pileup of charge. Such unstable interfaces usually reconstruct to restore their charge neutrality. The second origin of the interface polarity lies in the pyrroelectric and piezoelectric character of hexagonal SiC and wurtzite AlN and GaN. In these materials, the divergence of the macroscopic spontaneous and piezoelectric polarization across the interface induces the interface charge. The resulting electric field can influence the properties of devices. In this paper, we have studied the polar interfaces between the hexagonal crystallographic phases of SiC (i.e., 6H, 4H, wurtzite) and wurtzite AlN and GaN using the ab-initio calculations based on the pseudopotential method in the framework of the Local Density Approximation to the Density Functional Theory. The full structural relaxation has been performed and then the formation enthalpies and valence band offsets (VBO) of the resulting structures have been calculated. Further, we have investigated influence of the different reconstruction patterns at the interface on the resulting electric field. We find that the VBO's in the reconstructed structures are determined by the chemical composition of the interface and are nearly independent of the lateral arrangement and crystallographic phase of SiC substrate. Specifically, we predict possible intrinsic VBO's of the SiC/GaN and SiC/AlN [0001] heterostructures to lie in the range 0.7 – 1.7 eV, and 1.4 – 2.3 eV, respectively. Our studies show that SiC/AlN heterostructures are always of type I, whereas SiC/GaN heterostructure can be of type I or II depending on the orientation and chemical composition of the interface.

G11.35
POLARIZATION INDUCED 2D HOLE GAS IN GaN/AlGaN HETEROSTRUCTURES. Stefan Hackenbuchner, Jacek A. Majewski, Gunther Zandler, Peter Vogl, Walter Schottky Institute, Technical University of Munich, GERMANY.

The generation of high density 2D hole gases (2DHG) is crucial for further progress in electronic and optoelectronic nitride devices. Recently, it has been suggested that electric fields caused by the pyro- and piezoelectric character of the nitrides can induce a high density 2D hole gas at their interfaces. In this paper, we report extensive theoretical studies of the electronic structure of holes associated with the degenerate valence band and confined within GaN/AlGaN quantum wells and superlattices. The present calculations are based on a self-consistent solution of the multiband Schrödinger (6x6 kp model) and Poisson equation. The dependence of the eigenstates on the lateral wave vector has been taken into account and the hole density has been calculated by integrating over the lateral Brillouin Zone. We find the 2DHG density to be mainly controlled by the polarization charge at the GaN/AlGaN interface. Other factors, such as the widths of barriers and wells, the temperature, the Schottky barrier height, heterostructure offsets, and details of the doping profile play a minor role. Our calculations for a GaN/AlGaN gated heterostructure with a homogeneously Mg-doped $Al_xGa_{1-x}N$ barrier demonstrate that the 2D hole density can reach values up to $1.5x10^{13}$ cm^{-2} for 30% Al concentration. In doped GaN/AlGaN superlattices, we find the 2DHG density to be quite low for short well and barrier widths but to increase significantly for thicker layers. We predict a maximal hole sheet density of roughly $1.5x10^{13}$ cm^{-2} for GaN/AlGaN superlattices with a 60 nm period. These results clearly demonstrate the spontaneous polarization in wurtzite type materials to provide a novel and efficient tool for designing and optimizing device characteristics.

G11.36
INFLUENCE OF INTRINSIC DEFECTS ON ELECTRICAL PROPERTIES OF GALLIUM NITRIDE FILMS. Vyacheslav Bondar,

Igor Kucharsky, Bogdan Simkiv, Lviv National Univ, Dept of Physics, Lviv, UKRAINE; Charles Hant, Univ California, Dept of Electric and Computer Engineering. Davis, CA.

Electro- and photoconductivity of gallium nitride films deposited by rf magnetron sputtering in relationship with substrate temperature and nitrogen partial pressure were investigated. It was found that increasing of substrate temperature or decreasing of nitrogen partial pressure during deposition is accompanied by increasing of conductivity. The obtained experimental dependencies of conductivity on substrate temperature and nitrogen pressure during GaN thin films deposition indicate on nitrogen vacancies as the most probable donor-type defects in these films which determine their conductivity. Our results show that increasing of GaN films conductivity with increasing of substrate temperature fits in activation-type behavior. It gives the possibility to determine the activation energy of nitrogen vacancies formation.. Obtained calculated value of this energy is 2.3 eV. Theoretical evaluation of neutral nitrogen and gallium vacancies formation energy in thermodynamically equilibrium conditions gave 3.2 and 8.11 eV, respectively. However, under non-equilibrium deposition conditions with gallium excess, the nitrogen vacancies formation energy may drop down to 1.1 eV. Therefore, our obtained experimental value of donor centers formation energy in GaN thin films correlates with theoretical value of nitrogen vacancies formation energy. When GaN thin films sputtered at substrate temperatures 820K, they were photosensitive with maximum of photoconductivity at 360-380 nm. Films sputtered at substrate temperatures higher than 900K showed the broadening of photoconductivity band with shift of maximum to 400-410 nm region. The reason could be, that at higher substrate temperatures during GaN films deposition the concentration of more complex defects may increase, in particular the complexes of nitrogen vacancies with other native defects of acceptor type (such as gallium vacancies). It may reveal in additional photoconductive bands in long-wavelength region of absorption edge and broadening of photoconductivity region

G11.37
GAS SOURCE MOLECULAR BEAM EPITAXY OF HIGH QUALITY $Al_xGa_{1-x}N$ ($0 \leq x \leq 1$) ON SILICON AND SAPPHIRE. S. Nikishin, V. Kuryatkov, G. Kipshidze, C. Jin, K. Choi, Ìu. Gherasoiu, L. Grave de Peralta, H. Temkin, Texas Tech Univ, Dept of Electrical Engineering, Lubbock, TX; T. Prokofyeva, M. Holtz, Texas Tech Univ, Dept of Physics, Lubbock, TX; A. Zubrilov, Ioffe Inst., St. Petersburg, RUSSIA.

We report the results of epitaxial growth experiments of $Al_xGa_{1-x}N$ ($0 \leq x \leq 1$)on Si(111) and sapphire substrates aimed at understanding the origin of cracking. We show that growth procedures described here result in thick layers of $Al_xGa_{1-x}N$ that are free of cracks. Layers were grown by gas source molecular beam epitaxy with ammonia. We show that the initial formation of a Si-N-Al interlayer between Si substrate and AlN layer, at 1130-1190K, results in very rapid transition to two-dimensional (2D) growth mode of AlN. The resulting AlN is completely relaxed at the growth temperature. This reduces the residual strain in subsequent layers of GaN and AlGaN and is complete elimination of cracking in thick layers of GaN. In the growth of $Al_xGa_{1-x}N$ we observe a systematic dependence of the surface morphology on composition and the growth mechanism of the buffer layer. In layers free of cracks, we find background electron concentration around (4-5) $\times 10^{16}$ cm^{-3} and mobility (400 ± 100) cm^2/Vs for ~ 2 μm GaN film thickness. In $Al_xGa_{1-x}N$ ($0.2 < x < 0.6$) the lowest electron concentration is around (2-3) $\times 10^{16}$ cm^{-3} for the film thickness of 0.5-0.7 μm. P-n junction have been formed on crack-free layers of GaN with the use of Mg. We will discuss electroluminescence measurements on the p-n structures formed on Si and sapphire substrates comparing cracked and crack-free structures.

G11.38
A NEW TYPE OF LONG RANGE ATOMIC ORDERING IN AlGaN FILMS. E. Iliopoulos, K.F. Ludwig, T.D. Moustakas, Boston University, S.N Chu, Lucent Technologies.

In this paper we report on two types of long range atomic ordering in AlGaN films grown by MBE. The first type, reported by our group previously [1], occurs along the closed packed (0001) planes during growth along the same direction, has a periodicity of a single atomic layer and is promoted by low temperature buffers and nitrogen rich conditions of growth. The second type of ordering occurs along the same planes, has a periodicity of seven atomic layers and is promoted by high temperature buffers and Ga-rich conditions of growth. The crystal structure of such AlGaN films was investigated by XRD and TEM microscopy. A structural model with a certain AlN and GaN sequence is proposed to account for the observed diffraction data. The dependence of the optical properties on these two types of ordering will also be addressed. [1] D. Korakakis, K.F. Ludwig, and T.D. Moustakas, APL 72 (1997)

G11.39
CHARACTERIZATION OF ION IMPLANTED GaN. B.J. Skromme and G.L. Martinez, Dept. of Electrical Engineering and Center for Solid State Electronics Research, Arizona State Univ., Tempe, AZ; L. Krasnobaev, Implant Sciences Corp., Wakefield, MA; D.B. Poker, Oak Ridge National Laboratory, Oak Ridge, TN.

The development of advanced device and circuit technologies in GaN will require a selective doping technology, and ion implantation appears to be the only such practical method in this material. Acceptor implants are of particular interest for JFET's, junction termination extension in high voltage applications, thyristors, photodiodes, and other devices. Here, we describe studies of p-type implants in high purity HVPE material, using acceptor species such as Mg, C, and Be. In order to optimize the activation, co-implantations with various species such as Ne, Al, P, and Ar were investigated to create additional damage and/or alter the stoichiometry. High temperature anneals were performed using sputtered AlON caps to suppress N loss, at temperatures up to 1300°C. Preliminary experiments at even higher annealing temperatures will also be described. The properties of the implanted and annealed layers were studied using low temperature photoluminescence (PL) to monitor and optimize activation. Co-implants of P were found to modify the acceptor levels introduced by Mg acceptors, creating apparently deeper levels. The other co-implants did not qualitatively modify the spectra, although intensity variations were observed. Activation of the Mg acceptors is found to be at least 50X better than that of C and Be, even in the co-implanted material. The behavior of the various acceptor-related PL features will be discussed in detail as a function of implantation and annealing conditions.

G11.40
A METHOD FOR GROWING GaN ON GLASS SUBSTRATES AT EXTREME LOW TEMPERATURE AND PRESSURE. T. Marek, H.P. Strunk, Institute for Microcharacterisation, Friedrich-Alexander-University Erlangen-Nuremberg, GERMANY.

We present a growth technique for growing GaN layers from Ga-solution onto commercial glass as substrates. We use a high vacuum chamber in which a plasma source produces a N beam from ions accelerated it to up to 5 keV. We direct this N beam into a Ga reservoire kept at 600 degree celsius. The incomming N species produce the Ga vapor component which reacts in the N-beam and deposits a GaN layer at a glass substrate nearby the reservoire.
The grown layers were investigated by optical microscopy (Nomarski differential interference contraste, NDIC). Selected areas are investigated by atomic force microscopy (AFM), reflection electron microscopy (REM) and transmission electron microscope in cross section (XTEM). Energy dispersive X-ray analyse (EDX) complement these investigations.
The GaN layers are polycrystalline, have a thickness of up to several microns and are almost stoichiometric. The presented growth technique is a low cost, very easy technique but very powerful for growing stoichiometric GaN layers. The area of growth in our laboratory was 2cmx2cm. Implications of these findings for modelling the crystal growth will also be discussed.

G11.41
CHARACTERIZATION OF GaN ON NANO-POROUS SEMICONDUCTOR SUBSTRATES AND SURFACES. J.T. Wolan, Dave C. Swalm School of Chemical Engineering, Mississippi State University, Mississippi State, MS; Y. Koshka and S.E. Saddow, Emerging Materials Research Laboratory, Department of Electrical & Computer Engineering, Mississippi State, MS; M. Mynbaeva, Ioffe Institute, St. Petersburg, RUSSIA; J.A. Freitas, NRL, Washington, DC; D. Tsvetkov and V. Dmitriev, TDI, Inc., Gaithersburg, MD.

In this study the outermost atomic layer, near-surface region, and film/substrate interface of air-exposed GaN epilayers grown on nano-porous semiconductor substrates has been investigated. Nano-porous SiC substrates and nano-porous GaN-on-6H-SiC substrates were fabricated by surface anodization in an electrochemical cell under UV illumination. GaN epitaxial layers were grown on porous SiC and porous GaN (P-GaN) by hydride vapor phase epitaxy. Growth by this nano-lateral epitaxial method is described. Angle-resolved X-ray photoelectron spectroscopy (ARXPS), Auger electron spectroscopy (AES), secondary ion mass spectroscopy (SIMS) and ion scattering spectroscopy (ISS) were performed. Calculations of the Ga-to-N ratios for epitaxial films of non-porous GaN verses porous GaN (P-GaN) are 2.04 and 1.07 respectively, indicating improved material stoichiometry for P-GaN. Structure sensitive techniques including scanning tunneling microscopy (STM), X-ray diffraction (XRD) as well as low temperature photo-luminescence (PL) and scanning electron microscopy (SEM) to examine crystal structure, surface morphology and film thickness were performed and will be presented.

G11.42
CHARACTERIZATION OF GaN MOS STRUCTURES USING PHOTOANODICALLY GROWN OXIDES WITH RESPECT TO FET DEVICE APPLICATIONS. D. Mistele, T. Rotter, R. Ferretti[a], F. Fedler, H. Klausing, O.K. Semchinova, J. Stemmer, J. Aderhold and J. Graul, Laboratory for Information Technology, University of Hannover, GERMANY. [a]Institute for Semiconductor Technology, University of Hannover, GERMANY.

We have fabricated MOS structures directly on n-GaN surfaces by forming Ga_2O_3 using photoelectrochemical (PEC) techniques. PEC can be used for smooth etching, defect sensitive etching, and also for oxidation of n-GaN layers [1]. The key advantages of photoanodically grown oxides are on the one hand the possibility of etching and oxidation within the same procedure (e.g. useful for gate recess technology). On the other hand less surface damage is introduced compared to conventional dry etching techniques or sputter deposition methods. The oxides characteristics depend on PEC conditions such as electrolytes concentration and applied voltage. Chemical and structural analysis of the oxide layers were done using Auger electron spectroscopy, surface profilometry and X-ray diffraction.
Typical IV-characteristics of the created MOS structures show a distinct diode behavior. The negligible reverse currents originate in a strongly depleted region in the underlying GaN. Forward characteristics reveal an isolating behavior of the oxides with resistivities up to 10^{11} Ωcm and breakdown fields exceeding 0.4 MV/cm. CV-measurements show also good performance within ± 4V at frequencies ranging from 1 kHz to 1 MHz indicating depletion and accumulation behavior for all measured frequencies. The small flatband voltage shift with frequency of the CV-curves reveals that only a low density of interface states was introduced by the photoanodic growth procedure. Triangular voltage sweeps exhibit small capacitance hysteresis even at elevated temperatures up to 160°C which confirms a small concentration of electron traps within the isolating gallium oxides.
Integration of the oxide formation in a MOSFET device fabrication process is typically hindered by the solubility of the amorphous Ga_2O_3 layers in acids and bases. We will show how to face this challenge using tungsten as a gate metal.
[1]T. Rotter, D. Mistele et al., Appl. Phys. Lett. **76** (26), 3923 (2000)

G11.43
STRUCTURAL ANALYSIS IN REAL SPACE OF $In_xGa_{1-x}N$ SINGLE QUANTUM WELLS BY COAXIAL IMPACT COLLISION ION SCATTERING SPECTROSCOPY. M. Sumiya, Dept of E&E Eng, Shizuoka Univ, Hamamatsu, JAPAN; K. Mizuno, M. Furusawa, M. Yoshimoto, Tokyo Inst of Tech, Yokohama, JAPAN; S. Chichibu, Inst of Appl Phys, Univ of Tsukuba, JAPAN; S. Nakamura, Nichia Chem Industries, Anan, JAPAN.

The intense luminescence from $In_xGa_{1-x}N$ single quantum wells (SQWs) has been considered as the recombination of excitons localized at certain potential minimum originating from the compositional fluctuation. Structural analysis of the SQWs has been required both for improving the device performance and understanding the optical properties of $In_xGa_{1-x}N$ alloys. In this contribution, the structures of $In_xGa_{1-x}N$ single quantum wells (SQWs) for the ultraviolet, blue, and green light emitting devices were investigated by coaxial impact collision ion scattering spectrocsopy (CAICISS). The device-quality $In_xGa_{1-x}N$ SQWs (x=0.05, 0.2 and 0.5) with 3nm thickness were deposited on on 3 μm-thick GaN layer by two-flow metalorganic chemical vapor deposition (MOCVD). He ion beam accelerated at 2keV was used in CAICISS system. After the time-of flight spectrum was detected at the normal incidence, the variation of In and Ga signal intensity was observed, changing the glancing and azimuth angle of He ion beam. Azimuth angular dependence of both In and Ga signals exhibited three-fold symmetry due to wurtzite structure. The alloyed In has Ga-face (c) polarity as well as the variation of Ga signal exhibited also c polarity. It was found that In atoms incorporated into $In_xGa_{1-x}N$ occupied the substitutional Ga site and had c polarity. Moreover, the degree of disorder in In atomic arrangement of SQWs with low In mole fraction was larger than that with higher InN mole fraction. This enhanced disordering of lower In fraction detected by CAICISS is consistent not only with the intense luminescence from $In_xGa_{1-x}N$ SQWs [1], but also with localization in the hole wave function resulting in larger band-gap bowing parameter [2].
[1] S. Chichibu et.al., APL 71, 2346 (1997), [2] L. Bellaiche et.al., APL 74, 1842

G11.44
IMPROVEMENT OF CRYSTALLINE QUALITY OF GaN LAYERS THROUGH REMOVAL OF SiO_2 MASK DURING LATERAL EPITAXIAL OVERGROWTH. Min Hong Kim, Yoonho Choi, Jaehyung Yi, Min Yang, Chinkyo Kim, Jina Jeon and Shi-Jong Leem, OE Team, Device & Materials Lab., LG Electronics Institute of Technology, KOREA.

Many researchers have tried to grow high quality GaN films with low threading dislocations for the optoelectronic and electronic applications. Lateral epitaxial overgrowth (LEO) has been found to be effective for the decrease in threading dislocations, resulting in longer lifetime in violet LDs and low leakage current FETs. However, crystallographic tilting and highly defective region in coalescence fronts in LEO GaN layers were observed. These defective regions were affected by lateral growth rate and mask materials. 2um-thick seed GaN layers were grown by LP-MOCVD on sapphire substrates. SiO_2 films were deposited by PECVD on MOCVD GaN layers and 9um-wide stripes with periodicity of 12 um were patterned along $< 110 >$ direction. The lateral overgrowth of GaN was carried out by LP-MOCVD at various temperature, pressure and V/III ratio. The crystallographic tilting of (0002) plane toward the perpendicular direction of the stripe mask was observed in standard LEO GaN layer. The tilting was presumed to come from the strain between laterally grown GaN and SiO_2 mask. To clarify the effects of SiO_2 mask, it was removed by wet etching just before coalescence occurred and an additional lateral overgrowth was subsequently carried out to complete the fabrication of a SiO_2-removed LEO wafer. The crytallographic tilting was not observed in SiO_2-removed LEO samples and the FWHM of (002) and (102) peak was 180 and 250 arcsec, respectively. The width of defective area in coalesced fronts was about a few um in standard LEO samples, but the coalescence front of SiO_2-removed LEO samples was sharp and less defects, as observed by CL. We will report the properties of SiO_2-removed LEO GaN layers in detail.

G11.45
IMPORTANT PARAMETERS FOR THE SELECTIVE EPITAXY OF GALLIUM NITRIDE BY HVPE, THEIR INFLUENCE ON MORPHOLOGY, DISLOCATIONS, AND MICROSCOPIC LUMINESCENCE PROPERTIES. V. Wagner, O. Parillaud, H.J. Bühlmann and M. Ilegems, Institute for Micro- and Optoelectronics, Swiss Federal Institute of Technology, Lausanne, SWITZERLAND; S. Gradecak and P. Stadelmann, CIME, Swiss Federal Institute of Technology, Lausanne, SWITZERLAND; T. Riemann and J. Christen, Otto-von-Guericke University, Magdeburg, GERMANY.

Hydride Vapor Phase Epitaxy (HVPE) in combination with Epitaxial Lateral Overgrowth (ELO) has shown to be very promising to obtain thick high quality GaN layers with low dislocation densities on sapphire. We have studied the influence of the carrier gas (hydrogen vs. nitrogen), V/III ratios, stripe directions, and seed layer structures (crystalline vs. amorphous) on ELO growth and defect characteristics of GaN by HVPE. Growth was carried out on MOVPE-GaN/sapphire patterned with SiO_2 stripes, aligned along the $< 1-100 >$ and $< 2-1-10 >$ directions of GaN. The cross sections of the ELO-grown stripes range from triangular to trapezoidal to rectangular to inverse trapezoidal depending on the growth velocities on different crystalline planes. Under certain conditions lateral growth can be completely blocked. The growth mode can be modified during the deposition by varying the carrier gas composition. In the initial stage of growth, formation of triangular facets, using hydrogen/nitrogen as carrier gas, is preferred because dislocations that propagate vertically in the window region tend to bend by 90° when they reach these facets and continue then to propagate in the basal plane. In addition, by coalescence of triangular facets, the formation of voids is prevented. TEM observations show these bent dislocations and a high density of horizontal defects above the mask. After coalescence, the surface is flattened in a second growth step under nitrogen. Cross-sectional cathodoluminescence microscopy shows basically two distinct regions of luminescence intensity and nature. One showing near bandgap excitonic emission, the other a high intensity blue shifted emission band attributed to e-h-plasma recombination, indicating a high local free carrier concentration due to intrinsic defects or impurities. These two regions are correlated with different growth facets.

G11.46
A COMPARATIVE STUDY OF THE INFLUENCE OF THE LDA AND GGA APPROXIMATION ON THE CALCULATED PROPERTIES OF THE III-NITRIDES (110) SURFACES. H.W. Leite Alves, J.L.A. Alves, DCNAT-FUNREI, São João del-Rei MG, BRAZIL; R.A. Nogueira, DF-ICEx-UFMG, Belo Horizonte MG, BRAZIL; and J.R. Leite, DFMM-IF-USP, São Paulo SP, BRAZIL.

We calculated the LEED parameters and the surface band structures of the BN, AlN, GaN and InN (110) surfaces by means of the Full Potential Linear Augmented Plane Wave (FPLAPW) method (Wien97 code). We used both LDA (Ceperley-Alder model) and the GGA (Perdew-Burke-Ernzerhof model) approximations to the exchange-correlation term and compare the results. We find interesting qualitative and quantitative differences between the two sets of calculations. As a rule, the geometric LDA parameters are smaller than the corresponding GGA ones. In the case of InN, for instance, $\Delta_\perp$ = 0.21 Å(LDA) and 0.25 Å(GGA); ω = 11.4 degrees(LDA) and 13.0 degrees(GGA); the bond contractions at the

surfaces are 4.16% and 4.34% for the LDA and GGA, respectively. In connection to the band structures, the main differences refer to upward shifts of the occupied surface states of the LDA energies as compared to the GGA ones.

G11.47
DISLOCATION INDUCED WING ROTATION IN A THICK LEO GaN FILM ON SAPPHIRE. K.A. Dunn, S.E. Babcock, D.S. Stone, R.J. Matyi, Materials Science and Engineering Dept., University of Wisconsin-Madison, Madison, WI; L. Zhang, T.F. Kuech, Chemical Engineering Dept., Univ. of Wisconsin-Madison, Madison, WI.

Diffraction-contrast TEM, focused probe electron diffraction, and backscattered electron Kikuchi pattern (BEKP) analysis were used to investigate the systematic rotations of the crystal in the overgrown region ("wings") in a 16 micron thick coalesced MOVPE LEO GaN film.. A build-up of longitudinal dislocations with Burgers vectors $1/3[\bar{1}2\bar{1}0]$ and $1/3[2\bar{1}\bar{1}0]$ above the edges of the windows in the glass mask was observed by plan view TEM. These dislocations originate from loops that appear to nucleate at steps in the coalescence plane. As they expand away from the coalescence plane in the (0001), intersecting sets of $1/3[\bar{1}2\bar{1}0]$ and $1/3[2\bar{1}\bar{1}0]$ type dislocations often combine to form edge dislocations with Burgers vector $1/3\ [11\bar{2}0]$. In addition to the commonly observed "wing tilt" about the LEO stripe axis, (0.5 degrees about $[1\bar{1}00]$ in this case), a second rotation of the wings about the about [0001] axis was inferred from the Burgers vectors and arrangement of a second set of dislocations loops that form in the $(1\bar{1}00)$ plane in this thick sample. The rotation of the wings around [0001] has now been measured by focused probe electron diffraction, and the systematic nature of the rotation was confirmed BEKP over 7 bars (~85 microns). This rotation results in a lateral shrinkage of the GaN bar which is consistent with the compressive stress imposed on the film by the sapphire substrate.

G11.48
THE REDUCTION OF DISLOCATION DENSITIES IN THE TWO-STEP GROWTH OF GaN BY HVPE. P.R. Tavernier, E.V. Etzkorn, Y. Wang, D.R. Clarke, Materials Dept, UC Santa Barbara, Santa Barbara, CA.

One role of GaN hydride vapor phase epitaxy has been to grow thick films of GaN thereby reducing the number of threading dislocations which have been shown to degrade device performance. Previous work on the growth of HVPE GaN, using GaCl pretreatments or ZnO buffer layers, has demonstrated that the films are of very high quality films but the dislocation densities have not been reduced below a saturation level of $\sim 10^8$ cm^{-2}. The recent development of a two-step HVPE growth process has revealed a distinctly different behavior, namely that the dislocation density saturates at an order of magnitude or two lower (10^6-10^7 cm^{-2}) as thick film growth proceeds. We have thus found it possible to consistently grow high structural quality HVPE GaN by first depositing a low temperature nucleation layer by HVPE at 550°C and renucleating on this buffer layer at high temperature. Using x-ray mosaic spread data and PV-TEM we have observed the dependence of the dislocation density on film thickness. This can be understood by considering previously developed models of threading dislocation density reduction in terms of the formation and subsequent annihilation of mixed type threading dislocations.

G11.49
ORIGINS OF THREADING DISLOCATIONS IN GaN EPITAXIAL LAYERS GROWN BY OMVPE. V. Narayanan[1], K. Lorenz[1], W. Kim[2], and S. Mahajan[1,2]. [1]Department of Chemical and Materials Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, AZ; [2]Materials Research Science and Engineering Center, Arizona State University, Tempe, AZ.

The initial stages of high temperature (HT) GaN growths on low temperature GaN nucleation layers grown on c-plane sapphire has been investigated by transmission electron microscopy (TEM). Results indicate that even after 20s of HT GaN growth, islands of average height 100 nm and width 300 nm are dislocation free as confirmed by a conventional two-beam TEM analysis. After 75s of growth there still remains a number of discrete islands that are dislocation free (average height 300 nm and width 700 nm) and some that contain pure screw dislocations (c type) and mixed dislocations (c a type), while pure edge (a type) dislocations are absent. Both c and c a dislocations begin or terminate at the center of the island. Contrary to the previous suggestions by researchers, island coalescence may not give rise to pure edge dislocations (a type) as they are absent even after 2 minutes of HT GaN growth. Arguments will be developed to rationalize the above observations.

G11.50
THE CONTRIBUTIONS OF MICROSTRUCTURE AND IMPURITY COMPENSATION TO HIGHLY RESISTIVE GaN. A.E. Wickenden, D.D. Koleske, R.L. Henry, M.E. Twigg, M. Fatemi, J.A. Freitas, Jr., and S.C. Binari, Naval Research Laboratory, Washington, DC.

Highly resistive GaN films are an essential component of a variety of electronic and optoelectronic devices. Ideally, it is desirable to minimize the background donor level in the GaN film, and subsequently compensate with deep acceptors to achieve high resistivity in the unintentionally-doped (UID) GaN film and high mobility in intentionally doped n- or p-type films. Optimized MOCVD film growth has yielded UID-GaN films with resistivity $> 10^5$ Ω·cm, GaN:Si films with mobilities > 600 cm^2/Vs for n = 1x10^{17} cm^{-3}, and AlGaN/GaN HEMT structures with 2DEG mobility of 1500 cm^2/Vs for n_{sheet} = 1.2x10^{13} cm^{-2}. The resistivity of a GaN film is strongly influenced by growth conditions. Microstructural elements and impurity compensation contribute to the resistivity of UID-GaN films, and both components are influenced by epitaxial growth pressure as well as by nucleation layer process conditions. It is essential to identify and control the compensating centers that contribute to highly resistive GaN, as they can play a significant role in trapping effects observed in devices. We have observed that GaN grain size increases and carbon impurity incorporation decreases with increasing growth pressure, influencing the transport characteristics of the films. Resistivity has been observed to vary from $> 10^{10}$ Ω·cm to $< 10^3$ Ω·cm in UID-GaN films grown in the pressure range of 40 to 500 torr. The relative contributions of compensation due to microstructure and impurity incorporation will be discussed. Sponsored by the Office of Naval Research.

G11.51
MISFIT DISLOCATION ARRAYS AND FRACTURE IN AlGaN/GaN HETEROSTRUCTURES. D.M. Follstaedt, J.A. Floro, S.J. Hearne, J. Han, and J.J. Figiel, Sandia National Laboratories, Albuquerque, NM.

Tensile-strained $Al_xGa_{1-x}N$/GaN layers undergo a combined relaxtion mode in which cracks are introduced first, followed by the formation of a dense but well-ordered misfit dislocation network within the heterointerface. The combined density of cracks and misfits quantitatively accounts for the degree of strain relaxation observed using real-time stress measurements during metalorganic chemical vapor deposition. The competition between fracture and dislocation introduction appears to be determined initially by limitations on defect nucleation, where cracks are able to nucleate first at asperities in the AlGaN. However, once cracks do form, they aid the nucleation of misfit dislocations that can then rapidly glide large distances from the cracks. Misfit nucleation and glide ultimately accounts for the majority of strain relaxation. In the early stages of relaxation when the misfit density is low, dissociation of the misfits into partial dislocations is observed. Intersecting partials within the hetero-interface combine in a straightforward fashion. At later stages of relaxation, the misfit density appears to increase via multiplication processes whose nature has not yet been determined.

G11.52
DEFORMATION AND FAILURE MODES OF THIN FILM LAYERED SYSTEMS. Kai Wang, W.M. Ashmawi[a], M.A. Zikry[a], R.R. Reeber, Dept. of Materials Science & Engineering, NC State University, Raleigh, NC; [a]Dept. of Mechanical Engineering, North Carolina State University, Raleigh, NC.

Analytical and computational methodologies have been developed and used to characterize the effects of film thickness, interfacial stress and strain evolution, temperature, crystalline structure, and orientation on the growth, deformation, and failure of thin films in gallium-nitride/alumina and gallium-nitride/silicon carbide. New property measurements for thermal coefficients have been obtained and moduli empirically estimated for a broad range of temperatures. These are used in conjunction, with specialized finite-element computational techniques, to predict interfacial shear delaminations and tensile debonding on physical scales commensurate with thin film layered structures. It is shown that these computational methodologies, predictions, and material properties can be used as design guidelines to determine optimal materials and architectures for layered thin film systems.

G11.53
SURFACE ELEVATION AND STRAIN IN ION-IMPLANTED GaN. B. Molnar, S.B. Qadri, S. Schiestel, R.M. Stroud, C.A. Carosella, Naval Research Laboratory, Washington, DC.

Very few studies have addressed the stresses and strains associated with the ion-implantation process in GaN. One previous study of ion implantation indicated an increase in the out-of-plain lattice parameter in the damaged region. We report a systematic investigation of the elevation of the surface and X-ray strains of the ion-implanted GaN as a function of ion fluence, and the effects of these on other physical properties. Step height measurements between the implanted and the unimplanted surfaces were made by a KLA

Tenor, P10 profilometer. There is a sharp increase in step height for doses (~5x1015/cm^2) near to the amorphization level. For the same range of fluence we have found marked change in the etching of the GaN. Triple crystals X-ray measurements have been used to obtain the in-plain and out-of- plain lattice parameters. As the amorphization level is approached, the step height increase becomes an order-of-magnitude higher than determined from the measured out-of-plain strain measurement. In addition, the in-plain compression was found insufficient to account for the out-of-plane expansion. Transmission electron microscopy studies indicate void formation around the highly damaged (~Rp), region. We interpret the large increase of step height and the onset of etching as due to the expansion of the highly disordered region, where the stresses exceed the elastic limit and are relaxed by various mechanisms. This leads to micro-cracking and void formation. We observe that the relaxation processes are strongly affected by the microstructure of the GaN, and in turn can influence other properties of the GaN.

G11.54
ANALYSIS OF STRAIN AROUND THREADNG DISLOCATIONS IN GaN EPILAYERS BY DIGITAL PROCESSING OF HRTEM. S. Kret, P. Ruterana, V. Potin and G. Nouet, ESCTM-CRISMAT UMR 6508 CNRS-ISMRA, Caen, FRANCE.

The mosaic structure of GaN epitaxial layer (0001) on sapphire where studied by transmission electron microscopy. It was found that the distances of edge dislocations in the boundaries are variable. The geometric phase method of processing of HRTEM images was used for determining in plane components of strain fields generated by the dislocation network. Measurement performed for individual sub-grains shows quasi continuous misorientation changing across the grain and as large as 4 degrees for 30nm size grain where measured. The influence of strain field generated by individual dislocations on the sub-grain disorientation jump is analysed by using the map of local rotation of the crystal lattice. Analysis of strain tensor maps shows that for dislocation distances larger that 10 nm the interaction between dislocations is weak. Strong modification of strain fields of individual dislocation is observed when the distance are lower that 4 nm. The dislocation core distribution maps and in plane Burgers vectors components are derived from experimental strain tensor by applying the continual dislocation theorem. As expected, all the analyzed dislocations have Burgers vectors of type $1/3< 11-20 >$ oriented perpendicularly to the local boundary segment and most of them have dissociated core. The edge dislocations with compact core are found near the maximum curvature of boundary where the dislocation distances are small. On the straight parts mainly dissociated cores are observed.

G11.55
CLUSTERING OF InGaN/GaN QUANTUM WELL STRUCTURES. M.S. Jeong[1], J. Kim[1], S.J. Rhee[1], R.L. Strange[1], E.-K. Suh[1,2], Jeffrey O. White[1], H.J. Lee[2]; [1]Frederick Seitz Materials Research Lab. University of Illinois, Urbana, IL; [2]Semiconductor Physics Research Center, Chonbuk National University, Chonju, KOREA.

The InGaN/GaN quantum well (QW) samples grown by metal organic chemical vapor deposition (MOCVD) were investigated by near field scanning optical microscopy (NSOM) and time resolved photoluminescence (PL). The QW samples were prepared to have the similar PL peak positions with different PL intensities by changing the growth conditions. Although all the samples show the lateral variation of the PL intensity which is observed by NSOM, a few hundred nanometer size brighter regions are clustering each other and form a few micrometer size highly-luminescent region in the sample with higher PL intensity. While the PL intensity in the brighter region is 10 times higher than the darker region, the peak positions of both regions are the same. It indicates that the nonradiative centers are clustering and isolated from the highly luminescent region in the sample showing high PL intensity. It is confirmed by the time resolved PL result, which gave longer luminescence decay time in the sample with higher PL intensity. Thus it is concluded that the radiative region is well-separated from the nonradiative centers in the high luminescence efficiency InGaN layer.

G11.56
DEEP LEVEL DEFECTS IN OXYGEN DOPED GaN. J.M. Gregie, R.Y. Korotkov and B.W. Wessels, Materials Research Center and Department of MS&E, Northwestern University, Evanston, IL.

The formation of deep level defects in oxygen doped GaN grown by metal-organic vapor phase epitaxy was investigated. Using steady-state photocapacitance (SSPC) spectroscopy, three deep levels with optical ionization energies of 1.0, 1.4, and 3.25 eV were observed in both nominally undoped and oxygen-doped samples. Concentrations of the defects in oxygen doped films ranged from 3×10^{14} to 8×10^{15} cm^{-3}. The concentrations of the 1.0 and 3.25 eV level defects increased by about an order of magnitude upon oxygen doping, while doping had little effect on the concentration of the 1.4 eV level. From the measured concentrations the formation energies of the defects were calculated and compared to energies calculated using density functional theory.

G11.57
PLASMA-INDUCED EFFECTS ON THE THERMAL CONDUCTIVITY OF HYDRIDE VAPOR PHASE EPITAXY GROWN N-GaN/SAPPHIRE (0001). D.I. Florescu, Fred H. Pollak, Physics Department and NY State Center for Advanced Technology in Ultrafast Photonic Materials and Applications Brooklyn College of CUNY, Brooklyn, NY; William B. Lanford, I. Adesida, University of Illinois at Urbana-Champaign, Urbana, IL; R.J. Molnar, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, MA.

We have measured high resolution (2-3 mm) thermal conductivity (k) at 300K before and after plasma-induced effects on a series of n-GaN/sapphire (0001) samples fabricated by hydride vapor phase epitaxy (HVPE) using a ThermoMicroscope's scanning thermal microscope (SThM). The sample thicknesses were in the 40-50 mm range and the carrier concentrations ~8x1016 cm-3. The thermal conductivity before treatment was found to be in the 1.70-1.75 W/cm-K range, similar to that previously reported for HVPE material with this carrier concentration [D.I. Florescu et al, J. Appl. Phys., in press]. The samples were processed under constant Ar gas flow and pressure for a fixed time period. The only variable processing parameter was the DC bias voltage (125-500 V). After the initial 125 V procedure k exhibited a decrease linear in the DC voltage. At 125 V the thermal conductivity was only slightly less (k ~1.65 W/cm-K) compared to the non-treated case. k had dropped to ~0.3 W/cm-K for the 500 V situation. The implications of these results for device applications in the area of opto-electronics and high power electronics will be discussed. The Brooklyn College work was supported by Office of Naval Research contract #N00014-99-C-0663 and the New York State Science and Technology Foundation through its Centers for Advanced Technology program. The Lincoln Laboratory work was sponsored by the US Air Force under Air Force contract #F19628-95-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Air Force.

G11.58
EFFECT OF EXTERNALLY-IMPOSED RADIAL STRAIN ON THE PIEZOELECTRIC RESPONSE OF MOCVD-GROWN GALLIUM NITRIDE. Jennifer A. Himes, James R. Willis, and Daniel A. Gulino, Ohio Univ, Dept of Chemical Engineering and Condensed Matter and Surface Science Program, Athens, OH.

The large piezoelectric constants of GaN suggest possible application of GaN-based materials in piezoelectric sensors, among other areas. In this work, films of gallium nitride approximately 0.75 micron thick and grown by MOCVD were subject to an externally-imposed radial stress condition. Deposition was performed in a commercial MOCVD reactor (CVD, Inc.) at 1050°C using trimethylgallium and ammonia as the chemical precursors. The substrate was one-inch diameter silicon (111). After deposition, titanium dots were deposited in various locations, including the wafer center, by evaporation. Stress was applied to the film/substrate system using a modified micrometer head (Mitutoyo) mounted to an Ionic Systems Basic Stressgauge (model 30285). Stress levels were calculated based on the magnitude of the imposed deflection as read from the micrometer head display, and the piezoelectric response at any particular dot with respect to the center dot was measured by measuring the voltage difference using a digital multimeter (Keithley 175). The micrometer head impinged on the center dot and served as one electrical contact point. Effective piezoelectric coefficients were measured as a function of imposed radial stress. Applied stresses in the range of 1 to 5 GPa resulted in effective piezoelectric coefficients ranging from 0.6 to 2.0 x 10^{-5} C/m^2. A discussion of these results will be presented and comparisons made with literature values. The authors gratefully acknowledge partial support under ONR-DURISP N00014-96-0782, and J. Himes and J. Willis acknowledge partial support under AASERT N00014-97-0693.

G11.59
TEM ANALYSIS OF THREADING DISLOCATIONS IN ELO-GaN GROWN WITH CONTROLLED FACET PLANES. Noriyuki Kuwano, Kyushu Univ, KASTEC, Kasuga, JAPAN; Kayo Horibuchi, Kensuke Oki, Kyushu Univ, Dept of Adv Sci for Electronic & Mater, Kasuga, JAPAN; Hideto Miyake, Kazumasa Hiramatsu, Mie Univ, Dept of Electric and Electronic Eng, Mie, JAPAN.

It is known that threading dislocations have a strong interaction with facet planes to change their directions. Some of the present authors (HM & KH) confirmed the systematic changes in morphology of the facet planes of epitaxial-lateral-overgrown (ELO) GaN with the growth temperature T_g and the reactor pressure P_r. Behaviors of

threading dislocations in ELO-GaN with the controlled facet planes have been analyzed by transmission electron microscopy (TEM). A GaN film was grown by a low-pressure MOVPE method on a $[01\bar{1}0]$ striped a-SiO_2 mask fabricated on MOVPE-GaN/LT-GaN/ sapphire(0001). Two types of GaN films were made in a two-step sequence of switching T_g and P_r. They then had a two-layer structure: The lower layer was grown with vertical planes $\{2\bar{1}\bar{1}0\}$ or slanting ones $\{2\bar{1}\bar{1}2\}$. The upper layer of the both type specimens grew laterally to have a (0001) flat plane. In the former specimen with vertical planes, threading dislocations penetrate straightforwardly up to the exterior surface of the film. In the latter specimen with slanting facets, on the other hand, threading dislocations turn to the horizontal direction in the lower layer and gather up over the center of the mask-terrace. These results demonstrate that the morphology of threading dislocations can be controlled by choosing the growth conditions of T_g and P_r and GaN films of an extra-low dislocation-density can be obtained. The behaviors of threading dislocations in the specimens with a mask of a different size are also discussed.

G11.60
TRIGGERING THE FORMATION OF IN RICH QUANTUM DOTS IN InGaN/GaN SINGLE QUANTUM WELL BY USING In AS ANTISURFACTANT. S.J. Chua[1,2], M. Hao[1], P. Li[2], J. Zhang[2], W. Wang[1], W. Liu[2]. [1]Institute of Material Research and Engineering, Singapore, SINGAPORE; [2]Center for Optoelectronics, Dept. of Electrical Engineering, National University of Singapore, SINGAPORE.

The $In_xGa_{1-x}N$ alloys have been used as active layers of InGaN based blue and green light emitting diodes (LEDS) and laser diodes (LDs). Researchers have not reached consensus on the optical emission mechanism in InGaN/GaN quantum well (QW). There are two theories, one attributing to the InGaN quantum dots (QDs) and the piezoelectric effects or the combining effects of both. InGaN QDs can be formed by spinodal decomposition, Stranski-Krastanov (SK) growth mode, or using Si as antisurfactant. We report triggering or enhancing the formation of In-rich quantum dots in MOVPE grown InGaN/GaN single quantum well (SQW) by using In as antisurfactant. Two groups of $In_xGa_{1-x}N$/GaN SQWs were grown by MOVPE (Emcore D125) on (0001) sapphire substrates. MOVPE was conducted using TMGa, TMIn and NH3 as precursors. For the first group, a 2μm thick undoped bulk GaN was first grown on the 250$\AA$ thick GaN buffer layer. The growth temperature was 530°C and 1050°C for the GaN buffer and bulk layer, respectively. After deposition of the GaN bulk layer, the growth temperature was lowered down to about 760°C for the deposition of a low temperature GaN barrier and InGaN well. After growth of the SQW, a high temperature GaN cap was grown. H_2 and N_2 were used as carrier gases for the growth of GaN and InGaN, respectively. The growth conditions for the second group are the same as the first one except that before the growth of InGaN well, TMIn was flowed for a short time. Room temperature photoluminescence (PL) shows peaks at 420nm and 488nm for the first and second group of SQWs. The full width at half maximum (FWHMs) of the two peaks are around 20nm. We tentatively attribute the 68nm redshift to the formation of InGaN QDs or formation of larger QDs in the second group of SQWs. By flowing TMIn, In atoms act as antisurfactant in that they reduce the lateral migration of precursors. Besides, In atoms also act as nucleation centres for the QDs. However, the PL is very sensitive to the TMIn flow rate and time. Too large flow may result in In droplets rather than InGaN QDs. SEM shows that the morphology of SQWs is good without any inverted hexagonal pits (IHPs). TEM is being done to investigate the structure of QDs.

SESSION G12: LIGHT EMITTERS AND STRAIN CONTROL
Chairs: J. F. Schetzina and Michael A. Kneissl
Friday Morning, December 1, 2000
Room 210 (Hynes)

8:30 AM *G12.1
GROUP-III NITRIDE QUANTUM HETEROSTRUCTURES EMITTING IN THE WHOLE VISIBLE RANGE. Nicolas Grandjean, Benjamin Damilano, Jean Massies, CRHEA-CNRS, Valbonne, FRANCE.

Quantum wells (QWs) and quantum dots (QDs) have been grown by molecular beam epitaxy (MBE). The main physical mechanisms governing the optical properties of these quantum structures are related to the built-in polarization field and localization effects. Taking advantage of both these peculiarities, GaN/AlN QDs emitting light from blue to orange at 300 K can be easily facricated by MBE using the strain-induced islanded growth. The internal electric field, as high as 5 MV/cm, red-shifts the emission energy via a quantum confined Stark effect while the carrier localization in the dots allows 300 K photoluminescence (PL) despite the huge density of dislocations. InGaN/GaN QWs with In content larger than 15% also display 300 K PL in the whole visible spectrum from 0.4 μm to 0.66 μm. Giant Stokes shifts as high as 830 meV for sample emitting at 1.96 eV can be ascribed in part to localization effects. The strong carrier localization is further evidenced by especially designed samples and its origin will be discussed. Finally, this effect is used to realize single InGaN/GaN QW emitting white light.

9:00 AM G12.2
INTEGRATION OF $In_xGa_{1-x}N$ LASER DIODES WITH DISSIMILAR SUBSTRATES BY LASER LIFT-OFF. W.S. Wong, M. Kneissl, P. Mei, D.W. Treat, T. Schmidt, M. Teepe, and N.M. Johnson, Xerox Palo Alto Research Center, Electronic Materials Laboratory, Palo Alto, CA.

The combination of its high-temperature stability, similar crystal symmetry with the III-nitrides, and its relatively low cost has made sapphire the subsrate of choice in development of III-nitride-based blue laser diodes (LDs). The high thermal resistance of the sapphire substrate and the relatively high current densities combine to degrade the device performance and lifetimes due in part ot excessive heating during operation. Although substrates such as silicon or copper would be more ideal, direct deposition and fabrication of III-nitride-based laser devices on these materials are either unfeasible or result in poor quality devices. A more viable means of materials integration to improve the blue laser performance is by thin film lift-off and transfer of pre-fabricated, fully functional devices from sapphire onto another host substrate.
As a demonstration of this methodology, prefabricated $In_xGa_{1-x}N$-based multiple quantum-well (MQW) LDs on sapphire substrates were successfully transferred from sapphire onto Cu substrates. The separation of the LDs from sapphire was accomplished by using a laser lift-off (LLO) process [1] in which a single XeCI excimer laser pulse was directed through the transparent substrate. Heating the structure above the melting point of Ga (T_m=30°C) after laser processing completed the separation and transfer process. Characterization of the $In_xGa_{1-x}N$ LDs before and after the sapphire substrate removal revealed no measurable degradation in device performance. The threshold current, under pulsed ooperation, for a 3X500 μm^2 device and the laser emission spectrum remained essentially unchanged before and after the LLO process. Additionally, the conductive Cu substrate permitted fabrication and operation of a vertically-arranged LD using the Cu as a back contact. Electrical measurements from such a vertically-connected LD showed enhanced I-V characteristcs. Additional results from $In_xGa_{1-x}N$-based LDs fabricated with an epitaxial-layer overgrowth technique will also be discussed. The transfer of the $In_xGa_{1-x}N$ MQW LDs from sapphire onto Cu substrates demonstrates the efficacy of the LLO process to integrate these LDs onto virtually any sustrate material.

9:15 AM G12.3
UV EMITTER BASED ON HIGH-EFFICIENCY GaN/$Al_xGa_{1-x}N$ MULTI-QUANTUM WELLS. Motoaki Iwaya, Ryou Nakamura, Shinji Terao, Tsutomu Ukai, Dept. of E&E Eng., Meijo Univ., Nagoya, JAPAN; Satoshi Kamiyama, High Tech Reserch Center, Meijo Univ., Nagoya, JAPAN; Hiroshi Amano, Isamu Akasaki, Dept of E&E Eng., Dept. of MS&E and High Tech Reserch Center, Meijo Univ., Nagoya, JAPAN.

Solid state UV laser will surely give a big impact on the opto-electronics industry. Group III nitride is one of the best candidates, although, at the moment, fabrication of nitride-based laser diode is limited to wavelength longer than 375 nm. Increase of the effect of non-radiative component with increase of the AlN molar fraction in $Al_xGa_{1-x}N$ as well as the difficulty in achieving highly conductive p-type $Al_xGa_{1-x}N$ had obstructed the realization of UV laser diode based on nitrides. Recently, we succeeded in growing crack-free and high-crystalline quality $Al_xGa_{1-x}N$ by using a low-temperature (LT-) AlN interlayer, which was deposited on GaN/LT-buffer/sapphire. High-sensitivity flame sensor was demonstrated using this technique. However, emission efficiency of $Al_xGa_{1-x}N$ thus grown was still limited by the non-radiative components. Here we proposed a new growth process of fabricating high-quality and highly efficient UV emitter based on $Al_xGa_{1-x}N$. GaN/ $Al_{0.07}Ga_{0.93}N$ MQWs grown by this new technique contains threading dislocations as low as 5 10^7 per cm^2, which is lower than that in MQWs grown by the conventional process by more than three orders of magnitude. Emission efficiency of these samples was measured in detail by temperature dependent PL. Effect of Si doping was also investigated. At 30 K, all the samples showed almost the same PL intensity. However, at RT, their PL efficiency is completely different each other. Si doping is found to improve the PL efficiency at RT by one order of magnitude. In addition, reduction of threading dislocation density improves the PL intensity by a factor of 10. PL

intensity of low-dislocation-density Si-doped MQW is almost the same as that of $Ga_{0.88}In_{0.12}N/Ga_{0.99}In_{0.11}N$ MQWs for LDs. Control of conductivity, especially p-type doping will also be discussed. This work was supported in part by the Japan Society for the Promotion of Science "Research for the Future Program in the Area of Atomic Scale Surface and Interface Dynamics" under the project of "Dynamic Process and Control of the Buffer Layer at the Interface in a Highly-Mismatched System (JSPS96P00204)", and the Ministry of Education, Science, Sports and Culture of Japan, (contract number 11450131, 12450017 and 12875006).

9:30 AM G12.4
GROWTH AND CHARACTERIZATION OF AlGaN/GaN DBR MIRRORS FOR UV SURFACE-EMITTING DEVICES. Jung Han, Karen E. Waldrip, Jeff J. Figiel, Sandia Natl Labs, Albuquerque, NM; Hailong Zhou, Eleni Makarona, Arto V. Nurmikko, Div of Engineering, Brown Univ, Providence, RI.

Vertical-cavity surface-emitting devices are expected to improve emission directionality and beam quality. A vertical emitter in the UV would facilitate two-dimensional arrayed process that is of interest in miniaturized chemical and biological sensors. In this work we report the growth and characterization (both in situ and ex situ) of AlGaN/GaN distributed Bragg reflector (DBR) mirrors for applications in the UV spectrum range. One of the most challenging issues in growing nitride-based DBR mirrors is sample cracking due to tensile mismatch between AlGaN and GaN. Using an LT AlGaN interlayer on HT GaN, we were able to alter the initial strain from tension to compression, as verified by an in-situ stress monitor. The modulation and evolution of stress during the alternating growth of AlGaN and GaN layers was clearly resolved by the stress monitor. Nomarski microscopy from a 60-pair DBR structure (about 5 um thick) indicated smooth surface with cracks separated by at least 200 to 300 um; some areas imaged are completely crack-free. (0002) X-ray diffraction showed satellite peaks up to the 9th order. Reflectivities up to and beyond 99% have been measured in GaN/AlGaN multilayer DBR stacks in the wavelength range of 370-380 nm. The in situ DBRs have been incorporated into vertical cavity structures which include GaN:In active QW light emitter region and high reflectivity SiO_2/HfO_2 dielectric DBRs. We have studied the performance of these microcavities by photoluminescence and electroluminescence spectroscopy, and obtained cavity modal linewidths of 0.5 nm. Sandia is a multiprogram laboratory, operated by Sandia Corporation, a Lockheed Martin company, for the United States Department of Energy, under contract DE-AC04-94AL85000.

10:15 AM *G12.5
DEVELOPMENT OF NITRIDE LEDS AT LUMILEDS LIGHTING. S.A. Stockman, W. Goetz, N.F. Gardner, M.R. Krames, P.S. Martin, J.J. Wierer, D. Steigerwald, M.J. Ludowise, R.S. Kern, M.J. Peanasky, D. Bour, LumiLeds Lighting, San Jose, CA.

The luminous efficiency of InGaN-based LEDs now rivals or exceeds that of conventional lighting technologies. We will review the current state-of-the-art in InGaN LED technology, and highlight current challenges in MOCVD epitaxy, device design, and manufacturing. The primary advantages of LEDs over conventional lighting technologies are reliability and energy efficiency. However, the power limitations and high cost of LED-based lighting systems have so far prevented widespread adoption. In future LED lighting products, higher power and lower cost will be achieved by using a small number of high-power LEDs. These LEDs must operate at power levels approximately 10 to 100 times higher than those commonly available today, while maintaining excellent reliability and high efficiency. This requirement introduces a new set of considerations into the design and manufacture of InGaN LEDs, and we will present a preview of these future challenges.

10:45 AM G12.6
CURRENT INJECTION UV-EMISSION FROM InAlGaN MULTI-QUANTUM-WELL LIGHT-EMITTING DIODES. A. Kinoshita[12], H. Hirayama[1], M. Ainoya[12], Y. Yamabi[12], A. Hirata[2], Y. Aoyagi[1]. [1]The Institute of Physical and Chemical Research (RIKEN), Saitama, JAPAN; [2] Dept of Chemical Engineering, Waseda Univ, Tokyo, JAPAN.

Current injection ultraviolet (UV) emission from InAlGaN multi-quantum-well (MQW) light-emitting diodes (LEDs) is demonstrated. III-nitrides are currently of great interest for application to UV laser-diodes and LEDs. We have already revealed that InAlGaN alloy shows high photoluminescence intensity at room temperature in the UV range (300 - 350 nm). In this report, we demonstrate UV electroluminescence (EL) from InAlGaN MQW LEDs. The LED samples were grown at 76 Torr on the Si-face of on-axis SiC (0001) substrates by a metalorganic vapor phase epitaxy (MOVPE). The structure consists of a 200 nm-thick Si-doped $Al_{0.25}Ga_{0.75}N$ buffer layer grown on the substrate, a InAlGaN strain relaxation layer, three period of undoped $In_{0.05}Al_{0.34}Ga_{0.61}N/In_{0.02}Al_{0.60}Ga_{0.38}N$ QWs and 200nm-thick p-$Al_{0.25}Ga_{0.75}N$ layer with 20 nm-thick p-GaN capping layer. The thickness of the QWs and barrier layers are 2 nm and 6 nm, respectively. The growth temperature of the n-type layer, QWs and p-type layers were 1120°C, 720°C and 1050°C, respectively. After the growth, the LED samples were annealed at 820°C under flowing nitrogen (760 Torr) to activate the Mg acceptors. Ni/Au was used for the p, n-type electrode. The EL measurements were performed at room temperature under a pulsed current injection condition. The pulse widths were 1 μs with a duty cycle of 0.4%. The luminescence spectra were detected by a charge-coupled device system. The main emission peak is at 360 nm under 0.25 kA/cm^2. Although the thermal red shift was observed, the luminescence intensity has not saturated. We have demonstrated that InAlGaN alloy is significant material for the application to UV emitters.

11:00 AM *G12.7
CONTROL OF STRAIN AND DEFECTS IN NITRIDE MOVPE. Hiroshi Amano, Motoaki Iwaya, Shugo Nitta, Shinji Terao, Ryo Nakamura, Satoshi Kamiyama, Christian Wetzel, Isamu Akasaki, Dept of Materials Science and Engineering, High-Tech Research Center, Meijo Univ., Nagoya, JAPAN.

Control of strain and defects in nitride MOVPE is one of the most important issues for the fabrication of novel devices such as high-performance laser diodes in blue, violet, UV-A and UV-B region. In order to achieve both good optical confinement and crack-free film, we used thick AlGaN contact layer in a violet laser diode, and realized single peak laser beam in a vertical direction. The problem of strain and defects would be more serious if we move on to much shorter wavelength region. AlN containing alloys are much more sensitive to the non-radiative centers than InN containing alloys. Increase of lattice mismatch and impurity-enhanced stiffness increase foster the crack generation. Understanding the physical properties of nitrides at growth temperature gives a guideline how to realize high-quality and crack-free AlGaN alloys and their heterostructures. We achieved low dislocation density thick $Al_xGa_{1-x}N$ with x up to at least 0.45. PL efficiency of AlGaN at room temperature is much improved by reducing threading dislocation density. Devices based on these low dislocation density AlGaN will be discussed. We acknowledge Drs. T. Takeuchi, Y. Kaneko, S. Watanabe and N. Yamada, Agilent Technologies for help with the experiments. This work was partly supported by JSPS (JSPS96P00204) and MESSCJ (#11450131, 12450017 and 12875006).

11:30 AM G12.8
CONTROL AND ELIMINATION OF CRACKING OF AlGaN THIN FILMS USING LOW TEMPERATURE AlGaN INTERLAYERS. K. Waldrip, J. Han, S.J. Hearne, J.J. Figiel, G.A. Petersen, S.M. Meyers, Sandia National Laboratories, Albuquerque, NM; B. Gila, C.R. Abernathy, Univ of Florida, Dept of Materials Science and Engineering, Gainesville, FL; V. Krishnamoorthy, Major Analytical Instrumentation Center, Univ of Florida, Gainesville, FL.

The ability to produce short wavelength optoelectronic devices based on AlGaN has been severely hindered by cracking of the AlGaN layers due to the residual tensile stress in the films. We have demonstrated that the use of low-temperature AlGaN interlayers is effective in reducing the coherency stress when AlGaN is grown at high temperature on GaN pseudosubstrates. The stress evolution during growth was monitored using an in situ wafer curvature-based stress sensor and was correlated to ex situ high resolution x-ray diffraction and cross-sectional transmission electron microscopy analysis to determine the degree of coherency in the low temperature AlGaN interlayers. For 0.9um-thick AlGaN containing 20% aluminum, we found that the initial growth stress changed from tensile to compressive as the aluminum concentration in the AlGaN interlayer was increased. Furthermore, the crack density in the 20% AlGaN films shifted from very dense to crack-free, corresponding to the amount of aluminum incorporation in the interlayer. The onset of cracking was observed for an intermediate value of aluminum concentration in the interlayer. The microstructural and electrical transport properties, as well as the degree of relaxation in the AlGaN layer as a function of the aluminum content in the interlayers will be presented. Possible mechanisms for stress relaxation due to the interlayer will also be presented. One possible mechanism is that the low-temperature AlGaN interlayer is relaxed, and therefore serves to lower the coherency stress without degrading the structural quality of the high temperature AlGaN overlayer through misfit dislocations in the basal plane. The potential impact of the ability to use conductive AlGaN interlayers to provide crack-free AlGaN active layers in electrical and optoelectronic devices will also be discussed. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

11:45 AM G12.9
IMPROVED OPTICAL QUALITY OF BAlGaN/AlN MQW STRUCTURE GROWN ON 6H-SiC SUBSTRATE BY CONTROLLING RESIDUAL STRAIN USING MULTI-BUFFER LAYER. Hideo Kawanishi, Takayoshi Takano, Makoto Kurimoto, Yoshiyuki Ishihara, Masato Horie and Junichi Yamamoto, Kogakuin University, Dept of Electronic Engineering, Tokyo, JAPAN.

BAlGaN quatemary system grown on SiC substrate or AlN is one of a lattice matching nitride system with high potential use to light emitting devices from blue (350nm) to deep UV (down to about 200nm) wavelength region. However, it was complex to grow the BGaN, BAlN and BAlGaN, which include Boron in the nitride system, epitaxially on the substrates by Metal-Organic Vapor Phase Epitaxy. And optical properties of the epitaxial layer of the BGaN and BAlGaN grown directly on the SiC-substrate has to be improved for device applications.
For this purposes, (BAlGaN/AlN) MQW structure was grown on residual strain-controlled thin AlN layer using (GaN/AlN) Multi-Buffer layer. Crystal quality and surface flatness of the (BAlGaN/AlN) MQW structure were drastically improved by introducing the strain-controlled thin AlN layer with (GaN/AlN) Multi-Buffer layer, and shortest PL wavelength obtained from the (BAlGaN/AlN) MQW was as short as 245nm at room temperature. On the other hand, maximum Boron composition included in BGaN was 7%, from which room temperature PL spectral was obtained, in this time. But, the shortest PL wavelength of the BAlGaN quatemary was not strongly depended on the Boron composition, but also Al composition. However, optical characteristics of the PL spectra from the BAlGaN depend on the residual strain included in the epitaxial layer.

SESSION G13: LIGHT EMITTERS AND ELECTRONIC DEVICES
Chairs: Steve A. Stockman and Jung Han
Friday Afternoon, December 1, 2000
Room 210 (Hynes)

1:30 PM *G13.1
EUROPEAN ACTIVITIES ON GaN LEDS AND BLUE LASERS. Volker Härle, Georg Brüderl, Johannes Baur, Dominik Eisert, Stefan Bader, Berthold Hahn, Hans-Jürgen Lugauer, Andreas Weimar, Alfred Lell, OSRAM Opto Semiconductors, Regensburg, GERMANY.

The increasing interest in GaN-devices was focused on light emitting diodes for a long time. Since a couple of years more and more R&D activities have been shifted to laser development. The reason therefore is on one hand based on potential markets for GaN-based lasers such as data storage, printing, laser projection etc. On the other hand a more detailed technological basis for GaN materials with respect to growth and processing has been developed during the last couple of years, resulting in challenging laser data with low threshold currents, lifetimes in the order of 10.000 hours etc. Some main European activities are based on a cooperation of OSRAM Opto Semiconductors, the universities of Stuttgart, Braunschweig and Ulm, as well as the Fraunhofer Institut in Freiburg, resulting in first pulsed laser operation in July 1999. The work was carried out on SiC wafers using LP-MOVPE. The growth on SiC allows fast and easy processing due to the possible vertical current flow in such devices without using processes such as dry etching. Gain guided lasers with stripe lengths between 300μm and 1200μm and stripe widths between 3μm and 20μm were processed. Typical threshold current data in the order of 350 to 500mA for approximately 4μm x 450μm laser cavities were reached. Optimization on backside wafer thinning and developing of a cleaving process led to excellent laser facets. AFM measurements show a RMS value of less than 1nm. This means that 99% of the theoretical reflectivity of the facet can be reached (1). According to our knowledge best RMS values for dry etched mirrors are 3 to 4 times higher. Typical threshold current densities are below 20kA/cm^2. Lowest values for threshold currents of 330mA were reached at 416nm emission wavelength for 4μm wide and 450μm long stripes with mirror coatings of 98% and 70% reflectivity. Characteristic temperatures up to 280K indicate the good electrical confinement of our epi structure. On top of the laser results OSRAM Opto Semiconductors has demonstrated high brightness LEDs with more than 7mW at 460nm emission wavelength which is to our knowledge record for SiC based devices. These technological improvements indicate the competence developed at OSRAM. Acknowledgement: Part of this work was supported by the German Government (1) D.A. Stocker et al. APL 73 (1998) 1925

2:00 PM G13.2
IMPROVED OUTCOUPLING EFFICIENCY OF GaN BASED UV-LEDS. V. Schwegler, S. Schad, M. Seyboth, M. Scherer, C. Kirchner, M. Kamp, Dept. of Optoelectronics, University of Ulm, Ulm, GERMANY.

Currently there is a strong research interest on GaN-based light emitting diodes (LEDs) for the ultraviolet wavelength region. UV-LEDs in combination with luminescence converters are possible fundamental elements for production of white LEDs, which could replace common lighting components like incandescent lamps in the future. Although GaN (n_{GaN} = 2.4) has a smaller refractive index as most other III-V-semiconductors (e.g. n_{GaAs} = 3.5), improving outcoupling efficiency still poses a problem for device design. For UV emitting LEDs this problem is more serious since the absorption for smaller wavelengths increases and so multiple reflections in inappropriate geometries can decrease the device performance significantly. Whereas transparent contacts are already employed in LED manufacturing processes for GaN based LEDs, other techniques known from the GaAs based material system such as flip chip technique, substrate removal or advanced geometry designs (e.g. truncated inverted pyramides) have still to be evaluated and transferred. We evaluate the influence of transparent contacts on the IV- and LI-characteristics of UV-emitting LEDs. This includes in particular transmission measurements in dependence of metallization scheme (Ni/Au, Pt), metal thickness (5-15 nm, Ni/Au (4/6 nm): $\approx$45% transmission at 400 nm without annealing), and thermal treatment (N_2 vs. O_2 atmosphere). It is shown that external quantum efficiency is strongly depending on chip size and mesa geometry. A star-shaped structure is presented which allows improved outcoupling efficiency by 20-25% in comparison to standard design. The output characteristics of the examined devices were confered to simulations using a raytracer program. Material data for the calculations were extracted by absorption measurements. Simulations clearly show that removal of the substrate is a basic necessity for further increased efficiency. Flip chip technique of the devices is matter of current investigations.

2:15 PM G13.3
DEMONSTRATION OF ELECTROABORPTION EFFECT IN InGaN/GaN MQW LAYERS USING AN INTEGRATED LED/MODULATOR/DETECTOR DEVICE STRUCTURE. S.W. Chung, Y.S. Zhao, C.H. Lin, and H.P. Lee, Department of Electrical and Computer Engineering, University of California, Irvine, CA; W. Qiu, S. Zhang and G. Xu, Physical Optics Corp., Torrance, CA.

Being non-centro-symmetric, nitrides with Wurzite structure exhibit large piezoelectric effects when under stress along the c-direction (0001). The theoretical and experimental studies [1,2] on the quantum confined Stark effect (QCSE) for the strained InGaN/GaN quantum well (QW) shows that a strong piezoelectric field exists in the InGaN QW due to the lattice mismatch between the $In_xGa_{1-x}N$ well and GaN barrier layers. The strong piezoelectric effect and QCSE in the InGaN QW structures allow one to manipulate the free exciton absorption by the extrinsic electric field. However, most of previous studies are conducted at the material level based on optical measurements such as photoluminescence, photovoltaic and modulated electroabsorption[3], rather than on fabricated devices. In the present work, we fabricated a planner integrated three-section LED/electroabsorption modulator/detector structure on a $In_{0.16}Ga_{0.84}N$/GaN MQW LED wafer with a peak emission wavelength of 450 nm. In this structure, light is generated from the LED section and passes through the modulator section before being detected. The electrical isolation between adjacent sections is done using RIE. In designing the integrated structure, tapered structure was used to reduce diffraction loss between each section. The experimental results showed that the detector signal (at zero bias) due to the light emission from the LED section decreases monotonically with increasing negative bias from the modulator section for all injection levels at the LED. This result can be explained by a blue shift of the electroabsorption spectrum via QCSE when a reverse bias was applied to the modulator. The maximum quasi-modulation-efficiency between the detector and the modulator is found to be 22% at 15V reverse bias on the modulator for the $In_{0.16}Ga_{0.84}N$/GaN MQW structure. Work is currently underway to characterize $In_xGa_{1-x}N$/GaN MQW structure with varying In composition (and hence the piezoelectric field) at x of 0.1 and 0.27 respectively. 1) T. Takeuchi, S. Sota, M. Katsuragawa, M. Komori, H. Takeuchi, H. Amano and I. Akasaki, Jpn. J. Appl. Phys. 36, L382 (1997) 2) J.L. Sanchez-Rojas, J.A. Garrido, and E. Munoz, Phys. Rev. B 61, 2773 (2000) 3) S. Chichibu, T. Azuhata, T. Sota, and S. Nakamura, Appl. Phys. Lett. 69, 4188 (1996

2:30 PM G13.4
THE FABRICATION OF A HIGH POWER GaN METAL SEMICONDUCTOR FIELD-EFFECT TRANSISTOR. Seikoh Yoshida and Hirotatsu Ishii, Yokohama R&D Laboratories, The Furukawa Electric Co., Ltd, Yokohama, JAPAN.

GaN and related materials are very suitable for the electric devices which can be used under high-temperature, high-frequency, and

high-power conditions. GaN devices have large figure of merits for these purposes, since the GaN has a wide bandgap, a high breakdown field, a high saturation velocity. In this paper, a high-power metal semiconductor field effect transistor (MESFET) for operating at a very large current using GaN is reported for the first time. GaN was grown by a metalorganic chemical vapor deposition (MOCVD). Sapphire substrates were used for GaN growth. A GaN buffer layer was grown on the substrate. Undoped GaN, a Si doped active layer, and a contact layer were also grown on the buffer layers. After that, a GaN MESFET with a large size was fabricated. The 38 finger gates were used for large-current operation. The gate width was 8cm and the gate length was 2μm. The source and drain also had a multi-finger structure. The electrode materials of the source and the drain were Al/Au and the Schottky electrodes were Pt/Au. The multi-finger gate, source, and drain were isolated using SiO_2. The distance between the source and drain was 30μm. The FET structure was fabricated using a dry etching technique. Multi-electrode structures were also fabricated using SiO_2 for isolating the source, drain, and gate electrodes, respectively. The FET was operated at a current of over 5A. The breakdown voltage was about 400V. The transconductanse (g_m) was about 10mS/mm. The pinch off voltage was about -10V. We confirmed that this GaN MESFET can also be operated at a current of 10A. Therefore, a high-power GaN MESFET was thus demonstrated.

2:45 PM G13.5
LOW FREQUENCY NOISE IN GaN FIELD EFFECT TRANSISTORS. Sergey L. Rumyantsev, Nezih Pala, Michael S. Shur, Rensselaer Polytechnic Inst, Dept of Electrical, Computer, and Systems Engineering, Troy, NY; Remis Gaska, Xuhong Hu, Sensor Electronics Technology, Inc, Latham, NY; Asif M. Khan, Grigory S. Simin, Jinwei Yang, Univ of South Carolina, Dept of Electrical and Computer Engineering, Columbia, SC; Michael E. Levinshtein, Ioffe Institute, Sol St Electronics Division, St. Petersburg, RUSSIA.

We report on the experimental study of the low frequency noise in GaN Metal Semiconductor Field Effect Transistors (MESFETs) and Metal Semiconductor Oxide Field Effect Transistors (MOSFETs). The structures were grown by low pressure MOCVD on sapphire substrates. A $1.5\,\mu m$ undoped GaN layer was followed by the deposition of 60 nm GaN with doping level of $10^{18}\,cm^{-3}$. The transistors had a source-drain spacing of $4\,\mu m$ and a gate length of $1.5\,\mu m$. In order to fabricate MOSFETs 10 nm thick SiO_2 layer was deposited on one part of the wafer prior to gate metallization. The other part of the wafer was used for the MESFETs fabrication. At 300K, the spectral noise density of drain current fluctuations SI had the form of $1/f$ noise both in MESFETs and MOSFETs. At the low drain biases, corresponding to the linear regime of operation, S_I was proportional to the square of the drain current. The level of the $1/f$ noise was characterized by the Hooge parameter $\alpha = 10^{-3}$, that is one order of magnitude lower than it was reported before for GaN layers and comparable to that in typical GaN-based Heterostructure Field Effect Transistors. Measurements using Transmission Line Model (TLM) structures showed that the contacts did not contribute much to the low frequency noise. The analysis of the gate voltage dependencies of the noise allowed us to distinguish the origin of the noise among several possible mechanisms such as bulk noise, surface noise, noise from the space charge region under the gate. These dependencies showed that the noise originated from the GaN layer.

3:30 PM G13.6
DC CHARACTERISTICS AND MICROWAVE PERFORMANCE OF GaN-BASED MESFETS. R. Gaska, SET, Inc; X. Hu, G. Simin, Ahmad H. Tarakji, Asif Khan, J.W. Yang, USC, Dept ECE, SC; J. Deng, S. Rumyantsev and Michael S. Shur, RPI, Dept ECSE, Troy, NY.

We analyze the effect of low field mobility and series resistance on the DC characteristics and microwave performance of GaN-based MESFETs. Our calculations show that GaN-based MESFETs are less sensitive to the value of the low field mobility than to the source series resistance, especially for power microwave device with a large negative threshold voltage. Based on these results, we propose and implement a highly doped channel GaN MESFET that has a low source series resistance. Even with the low field mobility of approximately 100 cm^2/V-s and the gate length of 2 microns, these devices demonstrate the measured output power of approximately 3.4 W/mm at 2 GHz. Further improvements can be achieved with scaling down the gate length and the source-to-drain separation. We conclude that GaN-based MESFETs outperform GaAs-based MESFETs. Our calculations predict that short-channel (0.1 micron) GaN MESFETs might compete with GaN-based High Electron Mobility Transistors.

3:45 PM G13.7
AlGaInN QUARTERNARY LARGE PERIPHERY PSEUDO-MORPHIC HEMTS AND MOSHFETS. M. Asif Khan, Ahmad H. Tarakji, X. Hu, G. Simin, J.W. Yang, USC, Dept ECE, Columbia, SC; R. Gaska, SET, Inc., Latham, NY; S. Rumyantsev and Michael S. Shur, RPI, Dept ECSE, Troy, NY.

We report on large periphery pseudomorphic AlGaInN/InGaN and AlInGaN/GaN HEMTs and MOS-HFETs fabricated on sapphire and SiC substrates. Our results show that HEMT and MOSHFET performance is very close, with similar maximum drain currents on the order of 0.6 to 0.8 A/mm, similar cutoff frequencies, fT, and maximum frequencies of oscillations (with ft L product on the order of 12 to 16 GHz micron), etc. However, the MOS-HFETs have several orders of magnitude smaller gate leakage current and a lower 1/f noise. The maximum current scales almost linearly with the gate periphery for both types of devices, and the cutoff frequency does not change with the periphery scaling. The microwave power is proportional to the number of fingers. We also explore a doped channel design for minimizing the source series resistance and the microwave noise. CW and pulse microwave power data will be also presented. We conclude that pseudomorphic AlGaInN/InGaN and AlInGaN/GaN MOS-HFETs might have an advantage for applications requiring low 1/f noise and, as consequence, a low phase noise.

4:00 PM G13.8
Ta BASED OHMIC CONTACT ON ALGaN/GaN HFET STRUCTURES. D. Qiao, L. Jia and S.S. Lau, ECE Department, University of California at San Diego, La Jolla, CA; S.H. Lim and Z. Liliental-Weber, Lawrence Berkeley National Laboratory, Berkeley, CA; J. Barner, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Al/Ti based metallization is commonly used for ohmic contacts to n-GaN and related compounds. We have previously reported the development of an ohmic scheme specifically designed for AlGaN/GaN heterostructure field effect transistors (HFETs). This scheme, called the "advancing" contact, takes advantage of the interfacial reactions between the metal layers and the AlGaN barrier layer in the HFET structure. These reactions consume part of the barrier thus facilitating carrier tunneling from the source/drain regions to the channel region. The "advancing" approach leads to consistently low contact resistance of 1 Ω·mm or below on $Al_{0.25}Ga_{0.75}N$ (300Å)/GaN HFETs. There are two drawbacks of the this Al/Ti based advancing interface scheme, (i) it requires a capping layer for the ohmic formation annealing, (ii) the atomic number of Al and that of Ti are too low to yield efficient backscattered electron emission for e-beam lithographic alignments. For these reasons, we developed a Ta based "advancing" contact scheme for HFET structures. The presence of Ta in this ohmic scheme lead to efficient electron emission without requiring cap layers for the ohmic annealing. In this presentation, electrical and structural results will be discussed.

4:15 PM G13.9
METAL-SEMICONDUCTOR CONTACTS AND CPW MMIC ISSUES FOR AlGaN/GaN FETS. Bart Jacobs, Mark Kramer, Bram van Straaten, Fouad Karouta, Dept. of Electr. Engineer., Eindhoven Univ. of Tech., Eindhoven, THE NETHERLANDS.

This work will cover two different aspects of AlGaN/GaN MMICs. In the first part we report on our investigations on metal-semiconductor contacts to AlGaN/GaN FET structures. Both ohmic contacts (Ti/Al/Ni/Au) and Schottky contacts (Pt and Ni) were studied as a function of metal layer thicknesses, annealing conditions and several pre-metalization treatments. All experiments were done on wafers with identical AlGaN/GaN FET epilayer structure (sheet resistance of 550 Ohm/square, 25% Al). For the ohmic contacts, this has resulted in an excellent contact resistance of 0.3 Ohm mm. The systematic investigations, which led to this result, will be presented in detail. In addition to the studies mentioned above, we will also present Schottky contact behavior as function of different pre-metalization RIE processes. Influence of other plasma processes, like SiNx passivation, is also studied. Finally, we will report on AlGaN/GaN FET performance using the optimized contacts and compare these results to our non-optimized FETs. The second part of this work is devoted to coplanar waveguide technology. This technology is a possible solution for integrating several discrete FETs. As opposed to microstrip, CPW does not rely on a via-hole. However the target application, an X-band HPA, puts a number of constraints on the final CPW design. We will report on our investigations on CPW designs on AlN. The influence of effects like electro-migration, non-CPW modes, finite substrate thickness is discussed. The consequences for the matching network of a typical FET will be presented.

4:30 PM *G13.10
P-InGaN/N-GaN HETEROJUNCTION DIODES AND THEIR APPLICATION TO HETEROJUNCTION BIPOLAR TRANSISTORS. Toshiki Makimoto, Kazuhide Kumakura, Naoki Kobayashi, NTT Basic Research Laboratories, Kanagawa, JAPAN.

Recently, we have reported that Mg-doped InGaN layers show high hole concentrations above 1x10^{18} cm^{-3} at room temperature, i.e.,

maximum hole concentration of 7x10^{18} cm^{-3} was observed for Mg-doped $In_{0.14}Ga_{0.86}N$. These high concentrations are ascribed to lower acceptor activation energies and higher electrical activity of Mg atoms in InGaN. We have also reported that In atoms doped in p-GaN reduce the etching damage to form better p-type Ohmic contacts on the etched surface. Considering these characteristics along with lower bandgap of InGaN, p-InGaN is, therefore, a suitable material for a base layer of group-III nitrides based heterojunction bipolar transistors (HBTs). For the purpose of the HBT application, p-InGaN (100 nm) / N-GaN (500 nm) heterojunction diodes were grown to investigate their capacitance-voltage (C-V) and current-voltage (I-V) characteristics. The In mole fraction (x) in p-InGaN was changed from 0 to 0.25, while Mg and Si doping concentrations were fixed at 3x10^{19} cm^{-3} and 2x10^{17} cm^{-3} in p-InGaN and N-GaN, respectively. The C-V characteristics show the diffusion potential decreases with x, indicating that the valence band discontinuity between InGaN and GaN increases with x. The rectified I-V characteristics show that the ideality factors are around 2, indicating that their I-V characteristics are comparable to those of a p-GaN/n-GaN reference diode. Using these heterojunction diodes, an InGaN/GaN double heterojunction bipolar transistor (DHBT) was fabricated. The base thickness, Mg doping concentration and the emitter size were 80 nm, 1.5x10^{19} cm^{-3} and 30x30 μm, respectively. The maximum current gain of 1.1 was observed at room temperature. This relatively low current gain might be ascribed to high lateral resistance of the base layer. Optimal layer structures (base thickness and base doping concentration) and device design (the device sizes and the distance between base and emitter contacts) are expected to improve the InGaN/GaN DHBT characteristics further.