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
200 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 more thorough understanding of the band structure, defect structures, thermal expansion properties, 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.

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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, Rameshwar Waday, Ling Zheng, Jingli 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 trimethylgallium, (CH₃)₃Ga, and ammonia, NH₃ which readily leads to the formation of more complex gas phase products, such as (CH₃)₂Ga(NH₂) = 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 trimethylamine to the gas phase, (CH₃)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 trimethylgallium in hydrogen do not participate in such high temperature reactions. The pyrolysis of (CH₃)₃Ga and (CH₃)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 best gas reactions 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 kinetic 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 material properties and growth rates.

9:00 AM G1.2 SILICON AT [0001] GaN SURFACES: SURFACE STRUCTURES AND ADATOM KINETICS

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-GaN surface reconstructions as a function of the atomic chemical potential in the under-Nrich conditions the thermodynamically stable reconstruction is a 2x2 reconstruction on a monolayer of Si on GaN which is incorporated in surface sites. In particular we find that a 2x2 structure consisting of a Ga sublayer on a monolayer of Si with a Si-Ga atom in the third layer is the most 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 minimize the number of Si-Ga 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 Ga (001) / GaAs(001) system. The basis of these calculations we will discuss the effect that Si has on the growth of GaN.


9:15 AM G1.3 DRASTIC REDUCTION OF THRENDING DISLOCATION DENSITY OF AlGaN ON SiC BY USING HIGHLY-Si-INCORPORATED ALGaN SUPERLATTICE (Mitsubishi Aminco)1,2, Atsushiro Kinoshita3,4, Akira Hirasa5, Yoshinobu Aoyagi1,6, The Institute of Physical and Chemical Research (RIKEN), Saitama, JAPAN; 6Dept of Chemical Engineering, Waseda Univ, Tokyo, JAPAN.

A new in-situ technique to reduce threading dislocation density (TDD) on AlGaN buffers within sub-micron grown is demonstrated. To date, some methods to reduce TDD such as ELO and Pendo-epitaxy were reported. These methods need complicated processes and several nanometers growth to make the flat surface. However, in order to prevent cracks, it is necessary to reduce the dislocation density within sub-micron grown, 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 entire 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 Al₁₋₋ₓGaₓN, n=5 nm buffer were grown at first. Then, six periods of SLs consisting of 20 nm-thick highly-Si incorporated Al₀.₅₀Ga₀.₅₀N and 80 nm-thick undoped Al₀.₁₀Ga₀.₉₀N layers were grown. Lastly 100 nm-thick In₀.₅₀Ga₀.₅₀N layer was grown to count TDD on the AlGaN surface. We estimated Si composition is up to 0.1% TDD on AlGaN grown without Si-incorporated SLs layer was 2x10^5 cm⁻² and 2x10^4 cm⁻², respectively. We also obtained similar effects on Al₀.₁₀Ga₀.₉₀ substrate.

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

We have previously demonstrated GaN quantum dot (QD) formation on pseudo-heteroepitaxial GaN/Si surfaces by the use of Si anti-surfactant [1]. Ordinal step-flow growth is changed to three-dimensionally growth modes by the use of Si anti-surfactant on AlGaN surfaces and thus this induces quantum dot formation. The detailed study on the mechanisms indicated Si-N masks with micro-meter order scale are responsible for the QD formation. Through the investigation we recently found that threading dislocations (TDs), which are formed in GaN buffer layers on AIN/6H-SiC (0001) substrates, were effectively terminated at the anti-surfactant treated interface, resulting in drastic reduction (factor of 10^5) 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 AIN/6H-SiC (0001) substrates and the Si feeding amount. After depositing ~0.5 micron-thick GaN film (GaN buffer-layer) TESi (~90 nm) with a H₂ carrier gas was introduced to the surface. The formation of this 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 of the dislocations were terminated at the GaN over-layer/GaN buffer layer interface by forming dislocation loops. The
TDs were terminated by the Si-N mask, where no GaN nucleation was kinetically possible as was seen in GaN QD formation. GaN overgrowth on such regions led to the formation of TDs and the formation of a new type of dislocations which extended along the interface. Such dislocations along the interface reacted with other TDs to create dislocation loops. The detailed mechanisms of TD termination will be presented elsewhere. As a result of TEM observation, 1] S. Trannk et al., Appl. Phys. Lett. 69, 4966 (1996). 2 M. Takeuchi et al., in this symposium.

10:15 AM *GL.5 ROLE OF HYDROGEN IN SURFACE RECONSTRUCTIONS AND GROWTH OF GaN: Chris G. Van de Walle, Xerox PARC, Palo Alto, CA; Jörg Neugebauer, Fritz-Heber-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 in the Ga-rich limit of 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 NH3 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 or filled Ga dangling bonds occur. Under N-rich conditions, resulting in the maximum number of NH bonds, we favor, 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 the adsorption of NH2 or NH. Under Ga-rich conditions, we find a variety of competing 2x2 reconstructions, whose stability sensitivity 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 as 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 *GL.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, S. Crawford, J. Han, Sandia National Laboratories, Albuquerque, NM.

The release of hydrogen during isochronal annealing and the associated activation of dopants were measured for Mg-doped, MOCVD GaN at temperatures from 700 to 1000°C and anneal times from 2 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 denutrix (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, H1, H2, interstitial N2, and the neutral MgH complex. The theoretical model was then incorporated into diffusion-reaction formalism to describe H behavior at elevated temperatures. Our experiments indicate strong surface barrier to H release, and this effect was potentially treated using a simplified physical picture wherein equilibration is slow and surface sites are rapid and recombination description 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 donor-H complexes somewhat more 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 accommodate multiple donors in the vicinity of deep defects. Progress in these ongoing studies will also be reported. Supported by the US Dept. of Energy, Office of Basic Energy Sciences, under Contract DE-AC03-76SF00098.

11:00 AM *GL.7 THERMODYNAMICS VERSUS KINETICS IN THE GROWTH OF GaN/AlN QUANTUM DOTS BY MOLECULAR BEAM EPITAXY. Bruno Duhaud, Guo Mu, Alain Bouret, Guy Feuillet, Nikos T. Spanos, Julia Simon, CEA, Département de Recherche Fondamentale sur la Matière 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 especially true in the case of the hexagonal phase, due to the presence of a large internal electric field. Although being field-dependent 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 mechanisms. We address this point by presenting here a complete study of the formation of QDs as a function of various 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 (PL). We have shown that a continuous change from a 3D (rough) to a 2D/3D (Strasnicky-Krstikow) and to a 2D (flat) growth front by increasing the Ga/N ratio or decreasing the growth temperature. Furthermore, we have demonstrated this: 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 growth of the GaN film 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 kinetic factors (high (low) GaN flux ratio conditions, the growth mode is 2D (Strasnicky-Krstikow) 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.


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 AlOx 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 0.3 eV blue shifted relative to the band gap of bulk GaN. Very little yellow emission was detected. This blue shift is shown not to be originating from 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 *GL.9 STRUCTURAL AND OPTICAL PROPERTIES OF GaN BULK CRYSTALS GROWN FROM THE LIQUID PHASE. M. Albrecht, M. Nerdig, and H.P. Strunk, Universität Erlangen-Nuernberg, Institut für Werkstoffwissenschaften, Mikrostrukturierung, Erlangen, GERMANY; V.A. Isakov, V. Sukhovskoy, and V.A. Dmitriev, PhysTech WBG Research Group, Ioffe Institute, St.-Peterburg, 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 realize such structures: i) growth from solution at high temperatures and high pressure, (ii) lateral epitaxial overgrowth, 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 (<1.02 cm⁻² in case of solution growth, <10⁷ cm⁻² in case of epitaxial techniques) all of them result in individual substrates. No large bulk single crystals have been realized 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 than 2 atm. The crystals are grown from GaN-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 dozens of mm. Apart from vacancies and single interstitial 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 seeders (if 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 [001] oriented 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 10^8 cm^-2 within the well-oriented parts of the wafers.

11:45 AM GL10
GROWTH OF SELF-SEeded ALUMINUM NITRIDE BY SUBLIMATION-RECONdensation AND SUBstrate PREPARATION

Aluminum nitride (AlN) has received attention as a candidate for III-nitride epitaxial 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. Scudder, 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 14 mm 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 1 cm^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 with 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 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 the different crystallographic orientations significantly influences the quality, number, and grains. Their crystallographic orientation is related to the crucible axis. Also, the coloration of the growing grains can vary from colorless to dark orange depending on the growth conditions. Even though there are not conclusive studies on its origin, our results indicate that this interaction pattern 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 P. Rao and Alan J. Reiner
Monday Afternoon, November 27, 2000
Room 210 (Hynes)

1:30 P.M. #G2.1
MOVIE GROWTH AND OPTICAL CHARACTERIZATION OF GaAs/AlGaAs/AlAs ALLOYS: ELECTRONIC DEVICES
K. Endo, Y. Iwata, and Y. Iwata, University of Tokyo, Tokyo, Japan.

Due to a large band gap bowing, the GaAs alloy is expected to be a narrow-band gap material for the heterostructure with GaAs, giving a conduction-band minimum larger than 26 meV. In our study, high-quality luminescent GaN films have been obtained with the N concentrations up to 3.1%, grown using MOVPE, using trimethylgallium, AsH3 and 1-lithium hydride as precursors. The X-ray rocking curve for the (400) reflection showed a single-peak nature of the GaN films. The grown film surfaces were mirror-like, but with a cross-hatch pattern for the N concentrations higher than 2.5% due to the large lattice mismatch (o.3%). Low-temperature (3K) photo-luminescence (PL) properties are excellent for all the samples (N=0.4%-3.1%), with a single n-type band edge emission peak without the defect-related deep level luminescence often found in previous reports. The near-band edge emission survives even at room temperature, consistent with high intensity. 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, i.e., 0.1 cc for N=1% and 1.7 cc for N=0.1% at 2 K to 32 cc for N<1% and 14 cc for N<2% 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 ~100 K, much like the emission associated with the N isoelectronic

traps in GaAs. Then, the PL intensity decrease tends to much slower one up to 300 K, like the emission associated with the free-electron band. The PL peak of GaAs at various n-type doping levels is shown in Figure, as an example of the various features measured with different temperatures. Such localization behaviour of the band-edge states is considered as essential in GaN alloys as far as the N-concentration up to a few percent is concerned. We have also found by spectrometric 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

III-VN compound semiconductors, such as GaNP, are very attractive for light-emitting diodes with a wider visible wavelength due to the high bandgap of the optical property in the region of violet to blue emission of GaN. In this paper the growth of GaNP using laser-assisted MOCVD is reported. In this method, we used a Ga-P laser in order to decompose source gases at lower temperature. Trimethylgallium (TMG), ammonia (NH3), and tertiary-butylphosphine (TBP) were used for the growth. The growth temperature was 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 GaNP was grown at 800°C-850°C. The surface morphologies of GaNP were improved when the growth temperature was increased to above 850°C. Using an analysis of secondary ion mass spectrometry (SIMS) and X-ray diffraction, the Ga/N ratio was confirmed as improved. We investigated the photoluminescence of GaNP: P at 7K, and 75K. A band-edge emission (382 nm) of GaNP was observed at 7K. This peak was shifted to 25 nm compared with the GaN band-edge emission. The composition ratio, x, of GaNP corresponded to be about 1%. This value of the Ga/P peak shift is larger compared with previous results reported values grown by MOCVD. It is suggested that GaNP can be expected for materials for blue-violet LED.

2:15 PM #G2.3
GaAs vs. BeGaAs ALLOYS: ELECTRONIC CHARACTERIZATION.
D. St. Pierre, R. Watanabe, and T. M. Gerlach, Institute for Microelectronics, Warsaw, Poland.

The incorporation of 1 atomic percent of nitrogen into GaAs reduces its band gap by as much as 0.15 eV. For this reason, GaMN alloys with 0.01 < x < 0.03 are receiving a considerable attention due to their potential optical applications in the infrared regime. Experimentally, we show a strong reduction of pressure coefficient of the band gap of GaAs-Nx 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 influence 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-Nx and BeGaAs. 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 NAs substituting atom there is a strong coupling with the lowest minimum at X, explaining the observed pressure anomalies. In contrast, in the case of the BGa substituting atom this coupling is forbidden by symmetry. The symmetry-allowed coupling occurs with the higher-energy state at X, but it is weaker, and the effects of B are weaker. As a result, the pressure is not as effective in shifting the direct to the indirect band gap at about 6 GPa is predicted.

2:30 PM #G2.4
ELECTRONIC STRUCTURE OF GaAs AND GaP 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 parameter calculations, we have investigated the electronic and optical properties of GaN and GaAs as a function of nitrogen concentration. In contrast to phenomenological models and the economic parameter calculations, our calculations reveal a strong non-linear coupling, and a strong non-linear dependence on the position of nitrogen impurities. We analyze the structure and evolution of the alloy conduction band terms in localized states arising from
isolated nitrogen atoms, nitrogen pairs, extended clusters, and their mutual interactions. At low nitrogen concentrations, gap states result from nitrogen donors with impurities. In these states, the conduction band minimum is not lowered. However, in the case of high nitrogen concentrations, the conduction band minimum is lowered due to a simple anti-crossing model.

2:45 PM G2.5

InGaN 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 quantum wells of InGaN alloy gives a unique possibility of semiconductor band engineering while preserving lattice match to GaAs substrate. InGaN, 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 cases of alloys like AlGaN. All existing theoretical model of InGaN predict that interaction between Nitrogen states and conduction band of the matrix leads to serious reorganization (or even splitting) of conduction band states. In this paper, we present the experimental study of conduction band anomalies observed in this unusual alloy. By means of optical absorption experiment performed on free standing layers of InGaN 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 (0.8–2.5 eV; 100–300 K). By comparing electrical Hall experiment and infrared reflectivity for differently doped samples we were able to deduce the density of states, conduction band edge 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 doped InGaN and their behavior under hydrostatic pressure. In this context some metastable effects resembling DX-like center behavior will be analyzed. [1] C. Skotheim et al. Appl. Phys. Lett., 76, 2010, (2000) [2] Shan, Walukiewicz et al. Phys. Rev. Lett. 82, 1999.

3:30 PM G2.6

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 atoms 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 internally segregate to the edges and interior of the vacancy islands, to sites where they form only 1, 2 or 3 bonds with In atoms compared to 4 bonds for bulk incorporation or 3 bonds for incorporation in sites on the [001] growth surface. This lateral segregation reduces the 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 scales of compositional fluctuations in InGaN films, thus providing a possible source of the bulk compositional fluctuations.

3:45 PM G2.7

The high intensity emission of InGaN based light emitting diodes has been attributed to the formation of quantum dots in the outermost layers. 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 thickness from 1 to 3 nm, the composition of the outermost layer of 15–20% allows to tune the emission wavelength and to control the visible spectrum from blue to red at 3.0 K. For their characterization, we have measured the local deformation of the lattice fringes and correlated it to the composition of the layers. This procedure uses the Vegard law and locally connects the lattice parameters to the composition of the layer. By taking the necessary care, it was possible to estimate the composition of the outermost layers of 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
ORGANIZED PHASE SEPARATION IN OPTICAL AND DOING PROPERTIES OF InAlGaN FOR UV EMITTING DEVICES. Hideki Hirasawa1, Atsuhiko Kinoshita1, Takuya Yamanaka1, Akira Hirsen2, and Yoshinobu Aoyagi3, 1Riken (The Institute of Physical and Chemical Research), 2Waseda Univ.

We for the first time demonstratestitute room temperature ultraviolet LED operating at room temperature (300 K) with high energy gap InGaN active layer, which is supposed to exhibit superior light emission compared to InGaN/GaN quantum wells, if it is able to produce the violet/blue light. So far we have synthesized a new series of InGaN quantum well structures with high, blue and violet light emitting diodes (LEDs) with average quantum efficiency of ~8%. We have demonstrated the proof-of-concept of this new LED and have also compared the device performance with that of the state-of-the-art InGaN/GaN quantum well devices. Our results show that the InGaN quantum well LED has a much higher internal quantum efficiency (~9%) than the InGaN/GaN quantum well LED (~3%). This is attributed to the fact that the InGaN quantum well LED has a higher bandgap than the InGaN/GaN quantum well LED, leading to a lower recombination rate and thus a higher internal quantum efficiency. The internal quantum efficiency of the InGaN quantum well LED is also higher than that of the InGaN/GaN quantum well LED, which is due to the fact that the InGaN quantum well LED has a higher bandgap than the InGaN/GaN quantum well LED, leading to a lower recombination rate and thus a higher internal quantum efficiency.

4:15 PM G2.9
PHASE SEPARATION IN GaN:Al QUANTUM DOTS. S. Beddie1, N. A. El-Masy2, S. LeBoeuf2, and M. Behbehani3, 1Electrical and Computer Engineering Department, North Carolina State University, Raleigh, NC; 2Materials 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 GaN:Al quantum dots. These GaN:Al quantum dots were grown in the temperature range of 800–840 °C in an atmospheric pressure MOCVD system. The alloy composition ranged from 0.0 ≤ x ≤ 0.05. The films were characterized using X-ray diffraction, transmission electron microscopy and SIMS. Highly regular self-assembled separated phases in the form of alternating layers were observed in these quantum dots. The structure is highly complex, with 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 covers the entire thickness of the quantum dot layer. This is in contrast with the separated phases observed in the ternary InGaN layers. We will report a model to explain this behavior.
phase separation and its impact on the optical and structural properties.

4:30 P.M. G2.10

COMPARATIVE ROLES OF AIN AND GaN NUCLEATION LAYERS IN THE GROWTH OF GaN BY METAL-ORGANIC CHEMICAL VAPOR DEPOSITION (MOCVD). M. O. Manasreh, Department of Electrical & Computer Eng., University of New Mexico, Albuquerque, NM; and P. S. Ho, A. C. Tran, and I. Ferguson, ECOMORE Corp., Somerville, NJ.

We have investigated the comparative roles of AIN 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, AIN NLS provide higher density of nucleation sites for the growth of GaN overlayers. Differences and similarities in nucleation mechanisms of high temperature GaN single layers on AIN and GaN NLS will be discussed. Atomic force microscopy observation on the progress of coalescence of high temperature GaN islands deposited on AIN 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 difference between the sizes and densities of high temperature GaN islands seen on the two types of NLS. Verification 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 MSEC grant 00181900.

4:45 P.M. G2.11

MECHANICAL EQUILIBRIUM DURING GROWTH OF InGaN LASER DIODES ON LATERALLY OVERGROWN GaN ON SAPPHIRE. Miguel A. Noriega, Paul Fini, James S. Stueck, Steven P. DenBaars, University of California, Santa Barbara, Department of Materials and Electrical and Computer Engineering, Santa Barbara, CA.

The morphological evolution of InGaN laser diodes on InGaN epilayers grown 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, the implementation of InGaN epilayers using a low temperature (LEO) and AlGaN/GaN modulation-doped strained-layer superlattices in the laser structure has 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. 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 threading window regions, but does not show spirals in the nearly-dislocation-free wing region. To investigate the origin and evolution of the spiral surface morphology, a growth interrupt study was performed on sapphire-coalesced LEO GaN grown on sapphire. The laser structure was grown on a wafer with a spiral InGaN/GaN/NiAs (multiple quantum well) MQW active region, and after the process was completed with a Mg-doped InGaN/GaN SL SLS cladding layer, the InGaN/GaN/SLS (multiple quantum well) MQW active region, and after the process was completed with a Mg-doped InGaN/GaN SL SLS cladding layer, the significant spiraling occurs during growth. The growth rate of the active region due to 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 smooths 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 optical and device properties.

SESSION G3: POSTER SESSION GROWTH AND CHARACTERIZATION
Monday Evening, November 27, 2000
8:00 P.M.
Exhibition Hall D (Hyenes)

G3.1 CATION-HYDROGEN COMPLEXES IN METAL-ORGANIC CHEMICAL VAPOR DEPOSITION GROWN GaN. M. O. Manasreh, Department of Electrical & Computer Eng., University of New Mexico, Albuquerque, NM; and P. S. Ho, A. C. Tran, and I. Ferguson, ECOMORE Corp., Somerville, NJ.

Localized vibrational modes (LVMs) of carbon-hydrogen complexes in metastable chemical vapor deposition grown GaN on sapphire were studied using a Fourier-transform infrared spectroscopy technique. The mid-infrared spectrum exhibits a structure in the region of 2960 to 2840 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 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 results in the formation of a C-H complex defect strongly on the growth conditions. Detailed 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. Agnès Trastenaudine, Eric Audel, Robert Cadoret, LASMEA, Aubière, FRANCE; Tanja Paskova, Bo Menn tone, 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 description 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 description of the GaCl₃ gaseous species. We discuss the role of the composition of the vapor phase over the substrate by analyzing the gaseous composition upstream and above the substrate as well as the growth rate. In each case, the computed supersaturation in the mixing and in the growth 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 GaCl₃ vapor phase. Experiments in a mixed nitrogen and hydrogen gas ambient were also performed. The partial pressure of the other gases obtained 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 GaCl₂ had to be taken into account.

G3.3 INCORPORATION OF MAGNESIUM AND BERYLLIUM DURING REDEPOSITION IN METAL-ORGANIC CHEMICAL VAPOR DEPOSITION OF GaN. Shu-Jen Chen, Institute of Materials Research & Engineering, SINGAPORE; R. Liu, A.T.S. Wee, National University of Singapore, Dept of Physics; K.J. Williams, G.D. Pet, 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/implasers and high-power electronic devices. A large interfacial mismatch between GaN and InN induces 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/GaN phase separation in InGaN/GaN quantum well structures may produce quantum dot-like features to induce the excitonic 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 InGaN/GaN superlattices were epitaxially grown with a thickness of 200 nm on a 3-mm-thick GaN grown on sapphire by metal organic chemical vapor deposition. They were studied by a combination of high resolution X-ray diffraction (XRD), photoluminescence, 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 wide energy range and were modulated by the interference effect. The excitation power dependence measurements clearly reveal 3-4 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/GaN films possess a high Zn concentration near the InGaN/GaN interface and non-uniform distribution of In content, while InGaN/GaN 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 VINCIAL 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 wurzite GaN films during initial stage nucleation and growth on vicinal SiC(0001) substrates. 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 times. 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 difference 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 is observed. Once the islands are coalesced, the vicinal film can be characterized by these 3D-structured surface terraces. As the deposition continues, the 3D-bunched steps dissolve into equally spaced, double bilayer steps. For a flat film, coalescence leads to formation of spiral mounds, each associates with a threading screw dislocation. We have analyzed the microstructure of the initial stage of growth on vicinal substrates, the evolution of their time will be summarized in this presentation.

**G3.6**

**GALLULUM NITRIDE FILMS FROM LIQUID PRECURSORS.** Manfred Puchinger, Thomas Wagner, Max-Planck-Institut fuer Metallfuerschung, Stuttgart, GERMANY; David J. Kisailus, Frederick P. Long, A Materials Department, University of California, Santa Barbara, CA.

In general, GaN films are grown by MOCVD or MBE techniques. The preparation of the processing has led to electronic device quality materials. GaN films can also be grown from liquid precursors. In this technique, precursors 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 substrate supports. Thin precursor films turned into faceted, epitaxial GaN layers (up to ca. 20 nm) on sapphire C- and R-plane substrates. Such layers may be used as buffer layers. However, treatment of thicker films resulted in polycrystalline GaN materials. The microstructure of the films was investigated by SEM and TEM.

**G3.7**

**STABILIZATION OF GaN METAL ORGANIC VAPOR PHASE EPITAXY.** Roman Y. Korotkov, Joel M. Gruge, and Bruce W. Wessels, Northwestern Univ., Dept. of Materials Science and Engineering, Evanston, IL.

GaN epitaxial thin films doped with Mg were grown by metalorganic vapor phase epitaxy (MOVPE). Mg-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 ± 0.2 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 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 EPILAYERS QUALITY USING IN-SITU REFLECTANCE MEASUREMENTS.** B. Ruffennach-Chor, M. Broy, O. Brini, J. Montchamp, C. E. Bals, R. L. Averkin, GES, Universite Montpellier II, Montpellier, FRANCE.

Although a tremendous amount of work has been done these last years on the nitride semiconductor, 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 surface 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 a really parameter, since increasing it above a given threshold does not affect further the re-crystallization. Surprisingly, the amount of ammonium present in the re-crystallization step has a determining effect on the re-crystallization 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 dramatic manner when changed by only 10°C. In-situ reflectance allowed us to tune precisely our process and to obtain GaN layers with 500 cm²/Ns electron mobility at room temperature and photoluminescence fullwidth at 1.7 meV at 4K for the donor-bound exciton.

**G3.9**

**MICROSTRUCTURE OF GaN GROWN ON (11-20) SAPPHIRE.** R. Rutenburg, F. Hoveg, G. Nues, ESYTM-CRIMAT, Institut des Sciences de la Matiere et du Rayonnement, CNRS, FRANCE; A. Wickenden, M. Twigg, D. Kolinske, 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 and preliminary optical experiments on layers grown on (11-20) sapphire. Inside the layers, the density of defects is comparable to that found in layers grown on top of (0001) sapphire. The growth mode is also mosaic with grain size over 1-2 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**


One of the most interesting application of wurzite gallium based nitrides compounds will be optoelectronic devices from 6.2eV (AIN) to 1.8eV (InN). This will depend on the possibility to grow wurzite AIGaN 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, phase separation and growth instabilities have been reported. The misfit between AIGaN is smaller (2.5%), one would expect better stable growth of AIGaN.
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 this method of AlN/GaN may be more complicated. Not only the wurzite lattice can be decreased to simple hexagonal by AlN/GaN ordering along the c axis, but the growth can lead to other types of stacking. 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 (XRD 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 10:3 ordering.

G3.10 GROWTH OF As-DOPED GaN AND N-DOPED GaN BY MBE

Carl S. Darden, Sergei V. Novikov, Tim S. Cheng, Richard P. Campion, C. Thomas Foxon, University of Nottingham, Astronomy, Amsterdam, Nottingham, UNITED KINGDOM; Andrew J. Wisset, 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 GaN substrates grown by molecular beam epitaxy (MBE). We have studied the growth of Nitrogen. GaN 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 study the structural properties of the material. Our findings indicate that As affects significantly the surface reconstruction of GaN. For unintentionally doped GaN samples, a (4 x 4) reconstruction associated with excess Ga atoms appears during cooling. However, with As-doped samples, a (2 x 2) main 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 monocrystalline film with pre-existing native step edges and the surface roughness is seen to improve with increasing As overpressure. AES reveals that the surface concentration of As in GaN samples is independent of the As flux during growth for the wide range of 10^4 to 10^7 cm^{-2}. With this observation, 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 GaN by a direct substitution of N and As atoms. The strong blue emission suggests that GaNAs may be a suitable replacement for InGaN in optoelectronic devices grown by MBE. We are presently extending our studies to examine the growth of N-doped GaN (As-rich GaNAs) on misoriented GaN substrates to study the possible influence of vicinal growth surfaces upon nitrogen solubility in the sapphire.


"Present address: Sumitomo Chemical Co., Ltd., Tsuchi, 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 (001) 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 by chemical vapor deposition of the Si[111] surface in C$_2$H$_2$. The surface roughness of GaN grown on Si[111] with a 2.5 nm-thick SiC film is needed to reduce the structure defects in GaN film because sticking faults and dislocations can originate from rough regions of the SiC surface. GaN films were grown under both N$_2$ and Ga$_2$N$_2$ conditions. Our results showed that the growth mode and microstructure of GaN depended strongly on the GaN flux ratios. Under N$_2$ rich growth condition, the growth mode was three-dimensional, GaN showed statistical roughening of the surface and characteristic columnar structures with growth of GaN. GaN growth with Ga$_2$N$_2$ flux was two-dimensional. GaN films with a flat surface and an almost sticking-fault-free microstructure were obtained. The time-dependent crystal morphology was influenced by the strengthening interaction between GaN and SiC[0001] at the first GaN 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 the GaN or As-rich GaN/AlN substrate and the GaN films. This work was supported by NEDO.
over the silicon dioxide, gap closure, GaN continuous vertical growth and then cool-down to room temperature. A series of numerical models have been applied to simulation and development at different stages. Lattice mismatch strain and temperature variation are considered as input parameters. Submodelling techniques are used to simplify the computations and improve solution accuracy. To circumvent this, we have undertaken 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 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.


Exposure of GaN to N2 plasma at \( \leq 400^\circ \text{C} \) 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. 70 (1997) 1; K.P. Lee et al., J. Appl. Phys. 87, 7667 (2000)). We have created 5000 A thick damaged regions in n- and p-GaN using ICP Ar plasma, and subsequently examined the effect of N2 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 nitrogen ion implantation for damage recovery is compared to thermal annealing and wet removal processes.

G3.17 INVESTIGATION OF BUFFER LAYERS FOR GaN GROWN BY MOVPE. 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. Viscanti, Virginia Commonwealth University, Richmond, VA; and Istituto per lo Studio di Nuovi Materiali e 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 MOVPE deposition, low temperature, medium temperature and high temperature AlN buffer layers are at the disposal of the grower. There are quite a few reports on the beneficial effects of low temperature AlN buffer layers and other reported in the available literature. The reports emanate from different laboratories and are strictly due to different parameters. We have undertaken an investigation wherein these variety of buffer layers were grown on nitrided sapphire substrate under similar conditions for a comparative analysis. In addition to the single buffer layers of both GaN and AlN varieties, some composite buffers including GaN buffer layers separated by GaN layers were employed. Structural analysis by high resolution X-Ray diffractionmetry, topographical analysis by AFM were carried out to assess the quality of those 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 Excitation 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 film GaN layers 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.


Low In incorporation efficiency in MOVPE and MBE of GaN is still a key problem for blue/green LEDs and laser technology. It is found to be sensitive to many factors: temperature/pressure growth conditions, gaseous atmosphere (amount of hydrogen), substrate (strain effects), etc. Experimentally, extremely high lateral non-uniformity is observed in MOVPE grown In-GaN epilayers attributed to phase segregation. In this paper we consider two phenomena affecting In incorporation - surface segregation and phase separation occurring during the epitaxial growth. In surface segregation is analyzed with a novel rate-equation approach verified by vast experimental and theoretical data available for MOVPE. In In-GaN growth temperature and strain in the In-GaN epilayer are found to be principal factors controlling In segregation. In the layers grown on sapphire or on SiC substrates the strain is purely relaxed due to a large defect concentration. Only growth temperatures 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.

G3.19 EFFECTS OF OXYGEN ADDITION IN INDUCTIVELY COUPLED Cl2/Ar PLASMA ON THE ETCH CHARACTERISTICS OF InN-METALIDES. J-Myun Lee, K-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, AlGaN, InGaN, and In0.1Ga0.9N for device application have been examined in an inductively coupled plasma reactor using Cl2/Ar/O2 as an etch gas. Etch rates and selectivities were strongly influenced by the flow rate of oxygen as well as the composition parameters. Etch rates as high as 4500 Å/min were obtained for GaN, 1850 Å/min for Al0.2Ga0.8N, and 420 Å/min for In0.1Ga0.9N membrane. Moreover, the etch selectivities of GaN and the In0.1Ga0.9N over the Al0.2Ga0.8N were as high as 34 and 32, respectively. These are the highest values ever reported for an InGaN film with a relatively low Al composition (x=0.1). An X-ray photoelectron spectroscopy analysis of the etched surface showed that an AlO bond was formed on the InGaN surface during the Cl2/Ar/O2 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 AlGaN and InGaN, observed by atomic force microscopy, was also influenced by the flow rate of oxygen. Furthermore, the leakiness currents in Schottky diode on InGaN surface which was selectively etched by Cl2/Ar/O2 plasma, were decreased compared to those etched by Cl2/Ar plasma, probably due to the suppression of preferential loss of nitrogen.

G3.20 SURFACE MODIFICATION OF CUBIC GaN BUFFER LAYER GROWN BY METAL ORGANIC VAPOR PHASE EPITAXY. Akira Nagayama, Saitama Laboratory, Japan Radio Co., Ltd., Saitama, JAPAN; Ryoji Kogawa, Jun Wt, Kentaro Otake, Hideharu Sawai, Eiko Takuma, Hisakazu Ichinose, Dept of Materials Science, University of Tokyo, Tokyo, JAPAN; Yasuhito Shiraki, RCAT, 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 non-polar GaN [001] surface were approximately one tenth of those along [110] direction. In GaN films grown on the surface tilted by 4° from the [1-10] direction, stacking faults were preferentially generated from GaN surface, and on the [111] 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 ammonia ambient. In the present paper, in order to investigate these anisotropic properties, the features of the buffer layer as modified thermal annealing are studied on the basis of atomic force microscopy (AFM) and transmission electron microscopy (TEM) observations. An initial GaN buffer layer of about 100nm thickness was grown at 700°C by low-pressure (160 Torr) MOVPE. Then, a 200nm-thick GaN buffer layer [LT-GaN] was grown at 580°C. During this growing of the substrate up to 580°C the buffer layer was exposed to either
hydrogen, or hydrogen plus arsine ambient. AFM observation shows the anisotropic surface modification on the surface tilted toward [110] (as step edge) and toward [100] (as top edge). In the GaN:As hydrogen plus arsine gas annealing for LT-GaN buffer layer, the step edge density of the LT-GaN buffer layer tilted toward [110] is less than the density on the surface tilted toward [110]. TEM observation reveals that stacking faults in GaN buffer layer with step edges of GaN surface have a few monolayers in height. It is suggested that the anisotropic transport properties are caused by the dependence of lattice relaxation at step edges.

G3.21

PHASE EQUILIBRIA IN THE METAL-AL-GaN SYSTEMS AND THE THERMODYNAMIC STABILITY OF SCHOTTKY CONTACTS TO n-AlGaN.

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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-GaN systems,

where X denotes a transition metal. As a further step in understanding the phase equilibria in AlGaN systems, we now present results of the phase equilibria in the X-AlN systems. There are fortunately more experimentally available phase diagrams for these systems than for the X-GaN 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 N2 gas. Important phases in the 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 N2 gas during processing. On the other hand, the stability of the early transition metal nitrides on AlN is relatively insensitive to temperature and N2 pressure. We follow these predictions with experimental studies of the thermal stability of Schottky barrier contacts to n-AlGaN.


G3.23

CRACK FREE MOVPE GROWTH OF GaN/AlN AND GaN/AlGaN MOS ELECTROLUMINESCENCE TEST STRUCTURES (ELT) ON (111) SILICON SUBSTRATES.


The advantages of the silicon (Si) substrate for the growth of AlGaN/AlN/GaN MOS to-capsule or to-saturate (C) 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 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 MOVCD system, using TMGa, TEGa, TMAl, TMIn, NH3, SiH4 and C2H2 as precursors. Reactor pressures of 300 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 overcome the problem of cracks by the growth of two 15 μm 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/μm. 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/AlGaN/ELT on [111] show bright luminescence were also grown. Electrical, optical and structural properties will be presented and correlated to the growth conditions.

G3.24

MULTILAYERED MOVPE GROWTH OF GaN BY METAL ORGANIC VAPOR PHASE OVERGROWTH METAL ORGANIC VAPOR PHASE PHASE TRANSITION CONTACT TO n-GaN ON 3C-SC/Si(111) SUBSTRATE.


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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 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 superlattices). 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. Single layer growth using superlattice buffer layer showed only oriented (0002) plane of GaN from the XRD analysis. Raman spectra showed that the E2 high mode agreed with the selection rule for both observed in all GaN films. The A1(LO) and E2(LO) modes were assigned for GaN grown without buffer layer, whereas the E1(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-acceptor pair (D-A) 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-A 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.

**G3.20**

**FLEXIBLE FABRICATION OF GaN MILLIMETER-WAVE TRANSISTORS**

Flexibility is a key technology for future electronics. In this study, we fabricated GaN millimeter-wave transistors on flexible substrates. The transistors were fabricated on polyimide substrates using a scalable process. The transistors showed high performance with a high gain and low noise figure. The results demonstrated the potential of flexible GaN electronics for applications in millimeter-wave communication systems.

**G3.27**

**MOVPE GROWTH AND CHARACTERIZATION OF SL-DOPED CUBIC GaN**

Sl-doped cubic GaN is a promising material for high-power electronics due to its high electron mobility and high breakdown voltage. In this work, we investigated the growth and characterization of sl-doped cubic GaN films grown by metalorganic vapor phase epitaxy (MOVPE). The films showed high crystal quality with low dislocation density. The electron mobility and Seebeck coefficient were measured and showed good performance suitable for high-power applications.

**G3.30**

**EFFECTS OF Si ON GaN ELECTRONIC PROPERTIES**

Silicon atoms in GaN can significantly affect the electronic properties of the material. In this study, we investigated the effects of Si doping on the electronic properties of GaN films grown by metalorganic vapor phase epitaxy (MOVPE). The results showed that Si doping can control the carrier concentration and mobility of GaN films, which is important for high-performance electronic devices.
respectively. This indicates that the growth mode was influenced by 6H-SiC surface structures. In addition, small pits were observed on AIN films grown on different 6H-SiC surfaces. These pits were aligned along steps on the AIN/etched 6H-SiC, while those were randomly distributed on the AIN/un-etched 6H-SiC. The density of the pits is smaller on the AIN/etched 6H-SiC than on the AIN/un-etched 6H-SiC. This indicates that the pits were originated in 6H-SiC surface steps. This is due to incomplete coalescence of AIN nucleus (kink issue) and the stacking mismatch between AIN and 6H-SiC at step edges [2]. The detailed formation mechanisms will be given by means of STEM and photoelectron diffraction [6] (2000). [2] S. Takanaka et al., Appl. Phys. Lett. 66, 37 (1995).

G3.31 VAPOUR PHASE SYNTHESIS AND CHARACTERIZATION OF GaN POWDER. Kankai Hori, Yoshihito Matsuo, Yuuki Matsuoka, Institute of Technology, Imaging Science and Engineering Laboratory, Yokohama, JAPAN.

GaN-based materials have potential uses in power phosphors for wide-angle displays because of their high luminous 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 in 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 by induction heating. The generated vapor was transported to the hot zone of 800–1100°C by a N2 carrier gas (0.5 slm) and mixed with a gas flow of ammonia (0.5 slm) and N2 (0.5 slm). The m-synthesized powder was a mixture of GaN powder and Ga metal. Ga metal fractions were separated 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, The average diameter, dav, increases with increasing T, e.g., dav of the samples synthesized at 800 and 1100°C were 0.6 and 1.4 μm, respectively. X-ray diffraction patterns for the samples synthesized at T = 1100°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, reflecting small dav.

G3.32 EFFECT OF SUBSTRATE MISORIENTATION ON THE LATERAL EPITAXIAL OVERTURNOVER OF GALLiUM NITRIDE. Cheolwoo Son, Ok Hyun Nam, and Yangjo Park, Samsung Advanced Institute of Technology, Suwon, KOREA.

Lateral epitaxial overgrowth (LEO) techniques are widely used for reducing the dislocation density in nitride semiconductors. This reduction of dislocation density is essential 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 large out-of-plane epitaxial growth. However, there are no detailed experimental results on the effect of substrate misorientation on the LEO process. Firstly we have grown 2 μm 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 μm window and 10 μm mask was defined in a direction of <1 1 20>. The growth parameters were chosen to obtain a completely coalesced microstructure to compare the surface morphology. The effect of the misalignment angle between the substrate and the surface was characterized for different growth conditions. As the misorientation angle increases from 0.1 degree, the surface morphology of the laterally epitaxially grown GaN layers becomes smooth. However, further increase of the angle from 0.1 to 0.5 degree results in a deterioration. The surface morphology of the GaN layers after LEO process. In addition to the surface morphology, the crystallographic tilting between two subgrains changed from a symmetric behavior into a asymmetric one with increasing misorientation angle. In this paper, we report the experimental results of the dependence of the LEO process on the substrate misorientation.


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The step flow growth of GaN by plasma assisted molecular beam epitaxy (RF-MBE) was investigated. The step flow surface morphology of GaN is readily obtained in metal organic chemical vapor deposition (MOCVD). In RF-MBE, however, the spiral hiklocks of GaN are dominantly formed due to the large driving force of spiral growth, even in the homoepitaxy on step-flow GaN templates. And the spiral hiklocks are correlated to the threading dislocations (TDs) with screw component. So reduce the spiral hiklocks, the suppressed TDs are the modification of spiral growth, which is considered to be effective. In this study, two approaches were performed for realizing the step flow growth in RF-MBE GaN films, i.e., the utilization of AIN multiple interlayers (AIN-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 AIN-MIL with 4 pairs of thin (above critical thickness) AIN and 5 pairs of 2um (below critical thickness) AIN layers, respectively were grown on GaN templates following RF-MBE growth. GaN on AIN-MIL played a role for blocking TDs propagation from GaN templates. It was verified by optical interference microscope (AFM) that the step-flow surface morphology was realized. This might be obtained because of reduced TDs with screw component by AIN-MIL. Next, GaN were grown with AIN-MIL mode, in which the surface migration of GaN atoms could be promoted. The step flow growth was also appeared never AIN-MIL was utilized. This result may show that the AIN-MIL mode enhances the step-flow growth to overcome spiral hiklocks formation and that the thermodynamic system in MBE growth mechanism is modified by the alternative supply of nitrogen and Ga.


Using a single ID model we show that aluminum and nitrogen are transported inside a growing crystal cell jointly via convection and diffusion in AIN 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 AIN becomes impossible. 3D modeling of AIN 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, pressure species fluxes are directed from the AIN 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 crystal cell. Another important feature of the AIN sublimation growth is significant effect of N2 adsorption kinetics on nitrogen incorporation into a-SiC. We simulate the kinetics of adsorbed species using temperature dependent nitrogen sticking coefficient extracted from the experimental data on free evaporation of AIN in vacuum. The kinetic effects lead 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 suppressed due to low diffusivity of aluminum in the nitrogen atmosphere. These conclusions are supported by the experimental data obtained in our study of AIN growth. 1D and 2D modeling is applied to find conditions providing high growth rates of AIN 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.


Wafer bonding of silicon has generally used Si02 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 Ge and Al to enhance the formation of substrates in Si for GaN growth. The substrate consists of a thin Si layer of 0.1 to 0.2 μm in thickness bonded to a handle wafer through the low melting point metal or metal alloy, often with a Si02 or SiNx layer between the upper wafer and the metal as a diffusion or reaction barrier. This substrate would eliminate the thermal expansion mismatches induced stresses upon
cooling from the elevated GaN growth temperature by maintaining a stress-free bond between the growing layer, stop the thin Si template layer, and the buffer wafer. The 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 determining the bonding strength. 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. A broadening of (hkl) rocking curves if measured in asymmetric diffraction geometry. While these experimental data are in agreement with theoretical reports [1], they must not be interpreted as coincidence in twist of the mosaic blocks forming the imperfect epitaxy. This is due to a clear change in shape of the reciprocal lattice points of the annealed layers pretaining a deterioration of m-plane lattice properties. Indeed, (hkl) rocking curves measured in the more appropriate skew-symmetric geometry became 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 biplanar 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 mismatch induced strain in the AlGaN layer [1]. J. Dominguez et al., Thin Solid Films 350 (1999) 295.

G3.36 GROWTH OF GaN THIN FILMS BY THREE-STEP MOCVD METHOD. Seong Won Kim, Tomoki Shibata, Masahiro Akutsu, Toshimasa Suzuki, Nippon Inst of Techn, Saitama, JAPAN, Takaashi Yamada, Kazuhiro Haga, Chubu Fud Co Ltd, Saitama, JAPAN.

Growth of GaN films on sapphire substrates with low-temperature (LT) GaN buffer layer changes from three-dimensional (3D) band growth mode to two-dimensional (2D) one. We applied a 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 38μm thick LT-GaN buffer layer were grown in an FT-EPIC D-125 multi-wafer rotating disc low-pressure MOCVD system under reactor pressure of 2000 Torr. During MOCVD growth of GaN, “in-situ” photo-reflectance monitor was used to know the transition from 3D/2D growth mode, i.e., reflectance traces change from 3D growth 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 condense. At first, we obtained the dependences of 3D/2D transition on V/H ratio and growth temperature. Reflectance traces in roughening and recovery stages significantly changed according to the V/H ratio and growth temperature. The higher the V/H ratio was and the lower the growth temperature was, the stronger 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/H 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.


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 nitridation parameters strongly affected the out-of-plane and in-plane orientation and microstructures of the ZnO films. Using rocking curves to estimate the dislocation density, it was 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 photosensitivity increases as well as (002) X-ray diffraction intensity 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 is quite beneficial for obtaining epitaxial 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. Klotter, S. Einfeldt, D. Hommel, H. Telke, University of Bremen, Institute of Solid State Physics, Bremen, GERMANY; T. Suzuki, M. Bock, High Pressure Research Center, Upstalsboom, Wunsiedel, POLAND.

The paper focuses on the impact of thermal annealing on the structural properties of GaN layers as well as AlGaN/GaN heterostuctures 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 780 to 1050°C and 1 kbar, 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. However, a broadening of (hkl) rocking curves if measured in asymmetric diffraction geometry. While these experimental data are in agreement with theoretical reports [1], they must not be interpreted as coincidence in twist of the mosaic blocks forming the imperfect epitaxy. This is due to a clear change in shape of the reciprocal lattice points of the annealed layers pretaining a deterioration of m-plane lattice properties. Indeed, (hkl) rocking curves measured in the more appropriate skew-symmetric geometry became 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 biplanar 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 mismatch induced strain in the AlGaN layer [1]. J. Dominguez et al., Thin Solid Films 350 (1999) 295.


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/H ratio of 1100 in order to get well defined sidewalls. Finally, the V/H 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 top of the stripes, however, as soon as the lateral growth is enhanced by changing the V/H 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, coherence of the wings of lateral growing GaN can be achieved with sufficient quality for electronic devices. 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. Liangzhong Liu, Bao Liu, Yong Shi, James H. English, 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 received, off-axis H2 etched, off-axis (0001) SiC with a 3C-SiC epitaxial layer, off-axis received, off-axis (0001) SiC with 6H-SiC epitaxial layer. The short and long-time growths for AlN sublimation nucleate and grow on all substrates. The AIN 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 bider side 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 on SiC based on the thickness and the growth temperature. In addition, the sublimation of AlN 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 more sublimation growth helps but does not change the growth mode.
G3.41 NUCLEATION OF GaN ON (0001) SAPPHIRE DURING MOVPE GROWTH: A HIGH RESOLUTION ELECTRON MICROSCOPY STUDY. F. Degner, P. Ruterana, G. Nouet, ESCTM-CHSMAT, Institut des Sciences de la Matière et du Rayonnement, Cen, 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 20th, 30th, 40th, 1min, 2min, 3min, and 4min at 1100°C. Then samples were annealed at 1100°C and evolved for 30 min. The analysis was made ex situ by AFM in order to analyze the surface morphology and next by HREM in order to determine the interfacial relationships and try to explain the growth mechanisms. Systematically, it was found that the thinnest layers were free of nucleation and had ordered planes parallel to (0001) surface. As the thickness is increased the transformation from hexagonal structure to take place and misoriented islands grow mainly in coexistence areas. During the remaining 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. Hienau, Institute of Physics, University of Magdeburg, GERMANY; B. Baumont, P. Gibart, CHEA-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 cathodoluminescence (CL) microscopy. A two-step MOVPE EPITAXIAL process is used. In the first step, a 2μm MOVPE buffer on sapphire substrate covered with a periodic mask of Si₃N₄-strips along [101] 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 ELOG-GaN, exhibiting specific growth domains, are revealed by cross-sectional scanning CL microscopy. The coherent 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 face 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 an incorporation of impurities as evidenced by the appearance of a prominent donor-acceptor-pair recombination band restricted to the regions of off-axis lateral overgrowth. At about 6μm distance from the mask abrupt transition from a novel low luminescence intensity and lineshape is observed for both samples. Above this transition, up to the surface, clearly distinguishable sharp (FWHM < 3 meV) excitonic luminescence lines (i.e. FX, D⁵(X)…) dominate the spectra both in between mask stripes and near the mask the crystallographic quality. In plan-view CL wavelength images mapping the local emission energy over an area of 32μm x 25μm we find E_ex = 3.49eV (σ = 0.02meV) and E_ex = 3.48eV (σ = 0.076meV) for sample A and B, respectively [1]. P. Ventegrand et al., JAP 87 [9], 4175 (2000).


Thin films of 0.78-0.85μm thick GaN were grown on sapphire [0001] substrates by rfplasma source MBE equipment. The GaN/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 15min thick AlN Buffer layer. Samples with a thinner 5μm AlN buffer layer and a 20μm 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. 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 17μm AlN buffer layers. The tensile stress was 0.5 GPa for the N-rich growth and 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 17μm AlN buffer was used. The compressive stress was reduced to 0.2GPa for a 5μm AlN buffer and become 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 PHASE TRANSFORMATION DOMAIN BOUNDARIES IN GaN. Ph. Kominou, J. Kiossoglou, E. Sarigiannidou, G. Dimitrakopoulos, Th. Kelamis, Th. Karkkis, Aristotle University of Thessaloniki, Physics Department, Thessaloniki, GREECE; S. Masunaga, A. Masunaga, FORTH/IESL and University of Crete, Physics Department, Heraklion-Crete, GREECE; G. Nouet, P. Ruterana, ESCTM-CHSMAT, UMR5085-CNRS, ISMRA, Cen, 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 rfplasma source MBE. Different models of each type of defects exist. The stacking faults along with Hoil and IDP 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 macroscopic 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.


Theoretically, the growth control of the quaternary alloys AlGaN should give the independent variation of the lattice constant and the band gap, opening the possibility for effective band gap engineering in a wide range. Besides, AlGaN/GaN InGaN tripled 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 AlGaN alloys require growth temperature higher than 1100°C. 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 MOVPE were only obtained by the faraday configuration. The incorporation 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 AlGaN by Plasma Induced Molecular Beam Epitaxy (PIMBE). We kept the flux of Ga, Al, and In as well as the nitrogen plasma constant and varied the growth temperature from 550 to 775°C in order to achieve indium concentrations varying from 4 to 15%. Reflection High-Energy Electron 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 (θ/2θ) and reciprocal space mapping. The alloy composition was determined by Rutherford Backscattering Spectroscopy (RBS). Results of Hall effect and capacitance-voltage (CV) profiling of AlGaN/GaN InGaN lattice matched and strained structures will also be presented.

G3.46 INVESTIGATION OF INITIAL GROWTH STAGE OF CUBIC GaN USING AlGaN AS BUFFER LAYER ON GaN [100] BY MOLECULAR BEAM EPITAXY. Ryosuke Kimura and Kiyoshi Tsuchida, Dept of Medial Science, Tokyo University of Science and Technology, Ueno, Chiba, Kitanasu-ku, Yamanashi, JAPAN.

Metastable cubic GaN (c-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 crystalllographic symmetry. Cubic GaN can be grown on GaN, and this flexibility of using InGaN buffers was found to be one of the important points for device fabrication due to its ability to be easily cleaved. We have
demonstrated highly pure cubic GaN epilayer growth using an AlGaNAs buffer layer grown on GaN [100] by molecular beam epitaxy. [4] In this study, we report on the layer thickness of the GaN epilayer is only 0.4 mm. 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-mixed molecular beam epitaxy (RHEED) was used for films growth using Si doped n-type GaN [100]. [2] By the three dimensional X-ray reciprocal space map measurement of the epilayer on a nitried Al0.25Ga0.75As buffer layer, we could not detect any peak corresponding to the substrate. These results indicate the crystal layer is the cubic (002) phase and does not contain any hexagonal phase. It was observed that the surface condition of AlGaNAs buffer layer influences the phase purity of epilayer. The surface, which was observed (1x1) RHEED pattern which is thought as As stabilized surface, leads to the phase pure 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 is now under way. References [1] R. Kimura et al. Proc. of ICCE-7, Tsukuba [1999] 1B3. 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. Kominos, Th. Kehagias, Th. Karakostas, Aristotle University of Thessaloniki, Physics Department, Thessaloniki, GREECE; G. Noutet, P. Ruterana, ESCI-TRIUMAT, UMR5658-CNRS, ISFRA, Cen, FRANCE; A. Amine, G. Georganakos, FORTH, Heraklion, Crete, Greece; M. 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 Al2O3 substrate. Most of the threading dislocations starts at the GaN/AlN interface while the inversion domain boundaries (IDBs) were starting from the AlN/Al2O3 interface. All the three types of basal stacking faults (BSF) were observed, i.e. 11, 12, 22, while two types of IDBs were detected related to the Hilt and the DIB 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 BSF near the free surface and just above the AlN/Al2O3 interface is observed. In the Ga-rich samples the density of BSF is also near high the surface but low close to the AlN/Al2O3 interface. IDBs are narrow and dense in the Ga-rich samples while wide IDBs are observed in N-rich samples.

G3.48


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 a n+2 close spaced rotating disk MOVPE reactor, highly resistive 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, recrystallization time of the nucleation layer, growth temperature and growth rate. As a result, a phase diagram derived from experimental data 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 straight forward in the case of certain parameters results in new problems. This point will be discussed. Finally, the quality and uniformity over 24 wafers of some highly resistive layers are evaluated through the characterisation of HFET devices.

G3.49

STRUCTURAL AND ELASTICITY-BASED PROPERTIES OF SiC-BASED HETEROEPITAXY: THEIR RELATION TO THE HETEROEPITAXY OF 3.5 NITRIDES. Pierre Masi, March

Rouhani Larijani, Michel Avenius, Groupe d’Etude des Semi-conducteurs, CNRS-UJMR 5580, Univ. Montpellier 2, Montpellier, FRANCE; Thomas Strueder, Jürg Postl, TH Ilmenau, Institut für Festkörperphysik, 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 the substrate is provided by SiC, which affords a better lattice matching and closer thermal expansion properties. For BN heteroepitaxy, a good choice of a substrate is the orientation 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 crystalline interfaces. 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 various InGaN/GaN (c-BN) grown by MOCVD on top of GaN/Al2O3 substrates. Rutherford backscattering spectrometry (RBS) and particle induced X-ray emission (PIXE), were used to probe the indium content distribution with high depth (~10nm) and 1 micron resolution. 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/annellation results combined with X-ray diffraction (XRD) measurements allowed the determination of both parallel and perpendicular strain components. InGa1-xN epilayers were found to be under tension in the growth direction (100) and under compressive stress 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 estimation, when XRD is used, as well as in the interpretation of optical characterisation results. [1] M.F. Wu, A. Vantomme, S.M. Hegg, G. Larouche, P. Dick, R. Jacob, and I. Meoeran, Appl. Phys. Lett. 74, 365 (1999).

G3.50

MULTIPLE ZeO/C-ZnMoO SUPERLATTICE HETERO- STRUCTURES ON SAPPHIRE BY PULSED LASER DEPOSITION. Ayaj Sharran, Alex Kiv, Jay Narayan, North Carolina State University, Dept. of Materials Science and Engineering, Raleigh, NC; John Muth, C.W. Teng, Robert Kozlov, North Carolina State University, Dept. of Electrical and Computer Engineering, Raleigh, NC.

We have recently synthesized single crystal cubic Zn, Mo1-xO (c-ZnMoO) films with varying Zn content (x = 0.0 to 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 Zero (001)/ZnMoO (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, optical spectroscopy and photoluminescence (PL). We have performed Z Pols imaging on these specimens to reveal the nature of interfaces and migration across the interfaces. The XRD results clearly revealed the $\alpha$-ZnO (0001) and $\alpha$-Zn$_2$MgO (111) type of reflections from the film. The optical transmission measurements revealed $\alpha$-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 and XPS results showed that the blue-shifted from the corresponding excitonic band-edge of bulk ZnO. The $\alpha$-Zn$_2$MgO being a stable alloy system as opposed to wurtzite phase, these results are consistent with 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 blue-shift.

G3.54 GROWTH OF BULK GaN CRYSTALS VIA VAPOR PHASE TRANSPORT: Hyunmin Shin, Raulo Schlesser, Zlatko Sitar and Robert Dow, 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. Fast-saturating 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 phase nucleation technique. The crystals grown by this technique were either needles or platelets depending on the process variables, i.e., growth temperature, pressure and NH$_3$ flow rate, etc. The largest lateral and vertical growth rates (100/µm/hr and 10000/µm/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.


At present, the quality of cubic GaN in inferior to hexagonal GaN for its metallability. 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 cleaned easily in the device processing, which can be compatible with the GaN-based devices. Recently, the growth of cubic GaN has been achieved. The 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 properties were investigated by atomic force microscopy (AFM) and scanning electron microscopy (SEM). The surface roughness resulted from large amount of stripes 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 biggest of each stripe just was the top of high density stacking faults. Therefore, it is distribute 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 diffraction method. The results of hexagonal inclusions and cubic microtwins measured in [1-10] direction were twice or more than in [110] direction.

G3.56 OBSERVATION OF DISLOCATION ETCH PITS IN EPITAXIAL LATERAL OVERGROWTH GaN. T. C. Wei, W.S. Lee, C.C. Lin, H.S. Chang, W.I. Lee, Department of Electrophysics, and Microelectronics, National Chiao Tung University, Hsin Chui, Taiwan, REPUBLIC OF CHINA.

This work investigates dislocation etch pits in epitaxial lateral overgrowth (ELO) GaN by wet chemical etching. A mixture of H$_2$SO$_4$ and H$_2$PO$_4$ was used as an etchant, and SEM and AFM were employed to observe the surface topography. For the as-grown 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 density 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 also illustrate the high density of surface dislocations, which is an imperfect coalescence between the two overgrowth fronts. Three kinds of etch pits were observed in the window 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 ANTISURFACANT MEDIATED EPITAXY. Manashi Takeuchi, Satoru Tanaka, Hideki Hirayama and Yoshinobu Aoyagi. The Institute of Physical and Chemical Research (RIKEN), Saitama, JAPAN and Institute for Electronic Science, Hokkaido University, Sapporo, JAPAN.

Drastic reduction of the dislocation densities in GaN films has been accomplished by our sophisticated MOVCD 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 area 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- and micro-measuring techniques such as Hall measurement, V-plotting, and so on becomes 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 SI-nitride, the anti-surfactant is Si, which was supplied with TESI. GaN overgrowth was consequently carried out on the anti-surfactant-treated GaN surface. The results of the small amount of the anti-surfactant introduction showed sufficient dislocation termination, however, the dislocation termination become more effective with increasing anti-surfactant amount, so that the dislocation densities were reduced to mid 10$^3$ 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 aomca have some harmful influences on the crystalline quality of the overgrown GaN layers.


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 region are still not available. So far, AlGaN/AlGaN quantumwells are needed. We investigated MOVCD grown GaN/AlGaN multiquonumwells (MQW) with different AI 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 AI content are arranged symmetrically around the superlattice peaks in $q_x$ direction. The distance of the satellite peaks corresponds to an in-plane periodicity around the 16.2 nm reciprocal space map around the (0004). (205) and (205) reflections the satellite peaks shift towards lower $q_x$ values, indicating a partial relaxation in the InGaN plane. We conclude that the AlGaN barrier induced strain in the GaN epilayer leads to the formation of quantum dot like tensile and compressively strained regions with a periodicity around 16 nm. Integral cathodoluminescence (CL) spectra showed a superlattice structure over a surface area of 14 µm x 9 µm exhibit broad (FWHM > 150 meV), however, very high-resolution CL spectra 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 regions 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.
G3.50
DIRECT OBSERVATION OF BULK AND INTERFACE STATES IN GaN ON SAPPHIRE GROWN BY HYDRIDE VAPOR PHASE EPITAXY. Stephen H. Gos, Leonard J. Brillson, Ohio State Univ., Center of Materials Research, Columbus, OH; David C. Lock, 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. Using cathodoluminescence (CL) and scanning cathodoluminescence 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 in the sapphire, a 510 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 the “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 mechanism at this interface area to link 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

The strain relaxation in two kinds of GaN epitaxial lateral overgrowth structure (ELOG) on Si(111) substrates are investigated theoretically, using the minimum 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 faceted stripes with triangular cross-sections. Using scanning cathodoluminescence spectroscopy we have observed fully relaxed GaN at the peaks of both ELOG. However, the blue shifts along the pyramid surfaces are in contrast to the red shifts from the faceted stripes. The correlation between the results from scanning cathodoluminescence spectroscopy on the hexagonal mask and the theoretical modelling of the strain relaxation on the other have been investigated.

SESSION G4: DOPANTS AND PROCESSING
Chair: James S. Speck and Tetsutake 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. Hoffmann, F.H. Letter, 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 from the early years of nitride epitaxy considered to be the origin of the n-type conductivity in undoped 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 with deep levels also involved in deep red luminescence 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:O. The compensating centres are most likely vacancy-type complexes.

9:00 AM G4.2
OPTICAL AND ELECTRICAL PROPERTIES OF Be-DOPED GaN

Beryllium, replacing Ga in GaN is one of the most promising candidates for the effective acceptor. In this work we concentrate on studying the physical properties of Be-doped bulk GaN crystals. A 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 10^12 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 sample (high concentration of Be). These effects suggest an importance of compensation of Be acceptors by O donors and resembles situation typical for Mg-doped bulk GaN crystals. The role of Be interstitials (Be_i donors) important for compensation in oxygen free epitaxial growth of GaN:Be, is less probable here due to its formation energy is higher than that corresponding to substitutional oxygen, ON. Additionally, the both types of highly resistive crystals, GaN:Be 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:Be. In particular, up to 300K strongly broadened heavy hole VB in PL, absence of PL in the yellow-orange luminescence 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 neither VII nor detectable concentration of V_Ga was found. Additionally, for a conducting bulk GaN the correlation between YL intensity and concentration of V_Ga was elucidated and this observation is in agreement with thermodynamic 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 by different dopants/n-type defects and codoping phenomena.

9:15 AM G4.3
STABILITY AND DIFFUSION OF BERYLLIUM IN INSTITUT J. Sasaki, T. Morishita, and J. Van der Ziel, Xerox PARC, Palo Alto, CA; J. Jungstegmeyer, 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 arise due to incorporation of Be interstitials (Be_inter), which act as donors. In bulk GaN, the formation energy of Be_inter 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_inter 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_inter. We use density-functional theory in the local density approximation, and norm-conserving pseudopotentials. Simulations ranging from 3.9 to 56 atomic percent in size were used to 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 anisotropic origins of this anisotropy will be discussed. We have also studied Be_Ga and Be_inter, 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 N00014981G0101.

9:30 AM G4.4

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 0.8 μm AlGaN/GaN heterostructures are grown by MBE on thick (250 μm) HVPE GaN templates. The dislocation density is at 5x10^8 cm^-2, determined by the HVPE templates. The mobility of the 2D electron gas is above 100,000 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. CV measurements show that N_p=N_D is as low as mid-10^14 cm^-2 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 of the dislocations prevents a consistent interpretation of the MBE growth conditions. Under Ga-rich growth, the dislocations appear as bumps, while under stoichiometric growth they appear as pits. Scanning Kelvin probe microscopy reveals 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 Jessy under reverse bias. We believe that this effect is due to the presence of NV light which can significantly change the I-V characteristics of these heterostructures. This effect is reversible with a long time constant and a strong bias dependence.

9:45 AM G4.5 CARRIER RECOMBINATION AT DISLOCATION IN ENDBVENTED GaN SINGLE CRYSTALS: M. Albrecht, H.P. Strunk, Universität Erlangen-Nürnberg, Physikalisch-Chemisches Institut, Erlangen, Germany; J.L. Weyher, University of Nijmegen, RIM, Experimental Solid State Physics, Nijmegen, Netherlands; I. Gregory, S. Porowski, High Pressure Research Centre, Polish Academy of Sciences, Warsaw, Poland; T. Wasinski, Institut de Physique, Polish Academy of Sciences, Warsaw, Poland.

It is now well established that dislocations act as nonradiative recombination centres in group III-nitride based devices. However, not much systematic study exist that directly correlates the structure and properties of defects in the nitride materials with their electrical/optical properties. We find in this study a new form of nonradiative recombination due to the presence of stacking faults.

Dislocation (b=1/3<1120>) form and glide exclusively on polar (0001) and (111) glide planes. These results in a dislocation network in the (0001) plane formed by screws and 60° dislocations (b=1/3<1120>) with mutual intersection of screw dislocations during glide induces kinks on the dislocation lines, (iii) kinks either pin the dislocations or induce point defects (vacancies/interstitials) upon glide. Spatially and spectrally resolved cathodoluminescence performed in the scanning transmission electron microscopy shows radiation and nonradiative transitions at dislocations. Radiation recombination is observed at 2.4 eV, 2.9 eV and 3.3 eV. We analyse by high resolution transmission electron microscopy the dislocation structure and discuss the origin of the recombinant centres.

10:30 AM G4.6 IDENTIFICATION AND THERMAL STABILITY OF Ga VACANCIES IN ELECTRON-IRRADIATED Mg-DOPE GaN BULK CRYSTALS: K. Snarren, J. Nissim, Laboratory of Physics, University of Erlangen, Germany; L.A. Dunietz, Stanford, USA; J. Gregory, UNIPERS, High Pressure Research Center, Polish Academy of Sciences, Warsaw, Poland; D.C. Lock, Semiconductor Research Center, Wright State University, Dayton, OH.

Previous positron annihilation experiments [3,4] 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]. In this work we have applied positron microscopy to study the introduction of vacancies in Mg-doped bulk GaN crystals irradiated with 2 MeV electrons to the fluences (3-10) x 10^17 cm^-2 at 300 K. The increase of the average positron lifetime from 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 is a 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} and 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]. Interpretation of the results indicate that the irradiation-induced Ga vacancies recover in 30 min heat treatments at 500 - 600 K [1]. K. Snarren et al., Phys. Rev. Lett. 79, 2172 (2002) [2]. K. Snarren et al., Appl. Phys. Lett. 73, 2253 (2000) [3]. K. Snarren et al., Appl. Phys. Lett. 73, 2727 (1998) [4]. M. Wasinski, O. Sakai, Y. Ohno, H. Shinohara, and T. Matsushita, Phys. Rev. Lett. 84, 5602 (2000) [5]. T. Matsushita and R.M. Nemmle, Phys. Rev. B 55, 9571 (1997).


Although GaN has proven to be a suitable substrate for the growth of device-quality [Al,Ga]N heterostructures, the thermal, electrical and mechanical properties of GaN limit the performance and fabrication of light-emitting and laser diodes. Furthermore, the high growth temperatures required for this method 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, binary arrays based on finger-shaped microelectronic systems, and low-voltage 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 GaN to silicon without degrading the electroluminescence and I-V characteristics. This "pass-and-cut" process combines Pt-In transient liquid-phase (TLP) metal bonding with excimer laser lift-off (LLO) to transfer device heterostructures, including one or both cladding 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 integration process will be discussed. In particular, the control of the Pt-In reaction kinetics, its importance in acoustic impedance matching, and the role of the optical quality of the substrate will be emphasized.


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, Rc, 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 nitriding, 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 the 8 nm Ni/Au contact is replaced by the p-GaN surface using a method similar to Ref. 1. The sample is then heat treated by a 200 nm ITO film using reactive sputtering. The NiO/Au layer shows a Rs of 2x10^7 to 2x10^8 O-2, which is nearly 10 times lower than conventional Ni/Au and is unimplanted under consideration. Measurements on fully processed LEDs with NiO/Au/ITO CSL show an operating voltage of 4 V at 20 mA and a series resistance of 40 Ohm. 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: T. Maruyama, J. Cr. Sci. & Eng., C.C. Chau, C.N. Huang, and K-K. Shih, J. Appl. Phys., 64, 4491, (1989). T. Margaith, O. Buchaksy, D.A. Cohen, A.C. Abare, M. Hansen, S.P. DenBaars, and L.A. Coldren, J. Appl. Phys., 74, 3900, (1998).


While the role of extended defects in n-GaN optoelectronic devices has been studied in some detail, to date little is known about the effects of point defects on such devices, and for which level they are present. We show how a combination of deep level optical spectroscopy (DOLS) 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 DLTS/DLTS) are used for both test samples. Both test samples B show a decrease in decrease in emission lifetime compared to A, while the threading dislocation (TD) density from TEM analysis remains constant (≈4×1016 cm−2). EBIC analysis gives similar TD density and shows that the electrical activity of the TDs remains unchanged as with mismatch dislocations, PGaN or PSSG 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 was discussed.

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

1:30 PM #G5.3
APPROACHES FOR REDUCTION OF THE DEFECT DENSITY IN GROUP III - NITRIDE BASED HETEROSTRUCTURES.
T.S. Zheleva1,2, W. Ashmawi1, R.D. Vagones1, and K.A. Jones1.
1Sensors and Electronic Devices Directorate, US Army Research Laboratory, Adelphi, MD. 2North Carolina State University, Raleigh, NC. 3Department of Physics, University of Maryland, College Park, MD.

Lateral epitaxial overgrowth (LEO), pendeo-epitaxy (PE) and solid phase epitaxial recrystallization (SPEAR) will be discussed as three approaches for reduction of the defect density in group III-nitride based heterostructures. The increased interest in the phenomena of lateral epitaxy in the past few years is mainly due to the four-order 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 by MOCVD on sapphire, as well as on sapphire substrates using various mask materials. Studies of the LEO process using 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 faces 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. If the underlying GaN is etched in elongated columns/trenches, with orientation similar to that of the stripe in the mask at the conventional LEO process, the side walls of the columns provide the crystallographic template for the lateral PE growth of freestanding 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, reveal their remarkable similarity with vertically grown homoepitaxial material. These designs were grown with spatially varying growth temperature and GaN flux to control the density and migration of the GaN. Studies with TEM reveal that the 2θ-2θ x-ray diffraction patterns of the LEO-grown GaN films are similar to the 2θ-2θ x-ray diffraction patterns of the PE-grown GaN films. The improved crystallographic quality of the annealed LEO films is discussed in terms of lattice and thermal mismatch strain relaxation.

2:00 PM #G5.3
CAN LATERALLY OVERGROWN GaN LAYERS BE FREE OF STRUCTURAL DEFECTS? Zuzanna Lillienthl-Lawrence Berkeley National Laboratory, Berkeley, CA; D. Chen, H.H. Hills Physics Laboratory, Bristol University, Bristol, UNITED KINGDOM.

Lateral 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 weak peaks. To understand these extra peaks, transmission electron microscopy was applied to plan-view and cross-section lateral-overgrown samples. The GaN, 3 μm thick, was grown on Al2O3, followed by 1.5 μm of SiO2 stripes parallel to [1100] with 4.5 μm windows. These layers were overgrown by a 2 μm thick GaN layer. Studies in cross-section show much higher defect density at both homoepitaxial/laterally overgrown. The central parts of the overgrown areas had greater 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 n-type and mixed character with a large screw component, mainly originating at GL 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 part. Some of the threading dislocations present at the sides of the homoepitaxial regions bend to form in-plane segments in the overgrown region. We believe that these in-plane half-loops are formed in order to accommodate a tilt-twist at both interfaces. This tilt-twist leads to the addition of peaks in x-ray diffraction which is determined using large angle convergent-beam electron diffraction and is believed due to the different orientation expansion coefficients of GaN and SiO2 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. Motoigawa, K. Hirumitsu, Dept of Electrical and Electronic Engineering, Meiji Univ, Tama, JAPAN; Y. Iyeuchi, T. Meda, Taiiukun Research Laboratory, Sumitomo Chemical Co., Ltd, Taiiukun, JAPAN.

Epitaxial lateral overgrowth (ELO) with selective area growth is a promising technique to obtain high-quality GaN heterostructures. It is known 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 (Face Controlled ELO). In this paper, we report the FACELO GaN with threading dislocation (TD) density on the order of 106 cm−2. The ELO of GaN by an LP-MOVPE system was performed on a 4.0 μm thick (0001) GaN with SiO2 stripe masks along the <1100> 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 (1101), the SiO2 masks are buried by further lateral growth. In this FACELO, the TDs penetrate the ELO layer and come up to the surface, while the TDs are confined on the window area. On the other hand, when the first step of ELO has inclined facets of (1120), the lateral growth rate is increased in the second step of ELO. In this case, the TDs tend toward <1120> direction when the growth from ELO to FACELO. In this way, the TD density on the window area is remarkably reduced.
and that on total area is less than $2 \times 10^{-4}$ cm$^{-2}$. In order to reduce the dislocation density further, the double FACETOLO was demonstrated. The first layer with stripe SiO$_2$ masks along $150^\circ$ direction was performed by the 8-step process of the latter FACETOLO, and then the second FACETOLO with stripe masks along $10^\circ \times 90^\circ$ direction was also performed by the same growth process. The TD is dramatically decreased and the density is $2 \times 10^{-4}$ cm$^{-2}$.

2:30 P.M.  G5.4

MAPSING OPTICAL AND ELECTRONIC VARIATIONS IN LATERAL EPITAXIAL OVERGROWN GaN FILMS: Julia W.P. Hsu, M.J. Matthews, D.V. Lang, S. Richter, D. Akasaki, A.R. Kliman, and 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. Sputter-etch techniques are needed because different regions could contain different defects, impurities, and other species in the sample. Therefore, we report the optical properties of such GaN films. EDX results on cross-sectional LEO structures reveal five characteristics in different regions: the GaN seed layer, the nucleation regions, the wings immediately above the SiO$_2$ masks, the coalescence 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 GaN as the HVPE interfacial region: less in reverse bias, smaller SCM signal, and EF lower in the gap. Conformal Raman spectroscopy confirms a high density of carriers ($10^{19} \text{to} 10^{20} \text{cm}^{-3}$) in the wings. The coalescence regions have a lower carrier density, $\approx 10^{16} \text{cm}^{-3}$. The bulk film appears much lower doped, with a strong LO phonon peak and no hint of a phonon peak in the Raman spectrum. Since the wings are on the top of the SiO$_2$ masks, it is likely that the oxygen content is high in these regions and low in the interfacial region. We also find that the electrical 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 P.M.  G5.5


"Materials Dept., Univ. of California - Santa Barbara, Santa Barbara, CA, USA; Argonne National Laboratory, Argonne, IL; *Center for Applied Nanoscale Research, Argonne, IL; †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 substrate (seed) regions. Coalescence of wings from neighboring stripes may then generate additional extended defects. Although the exact origins of wing tilt are not known at the current time, it is obvious that the problem can be minimized using different growth techniques. 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 empirically 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 2-axis surface diffraction meter at the Advanced Photon Source. During LEO, wing tilt emerged early (< 600s) in the growth and rapidly reached a value of $\approx 1^\circ$, with an increase to $\approx 1.5^\circ$ after 3600s of growth. Upon cooldown to room temperature, tilt increased slightly to $\approx 1.3^\circ$, indicating that thermally-induced stresses at the wing/seed interface are not dominant in determining tilt magnitude. These results as well as complementary SEM and TEM measurements will be discussed, with emphasis on controlling LEO wing tilt via an understanding of its origins during growth.

3:30 P.M.  G5.6


We have reported the HVPE growth of thick GaN layers by a facet-initiated epitaxial lateral overgrowth (FIELD) method with low dislocation density of $10^4$ cm$^{-2}$. FIELO-GaNO substrate was successfully applied to the fabrication of InGaN MQW blue laser diodes (LD). In this paper, characteristics of FIELO-GaNO, in particular, that in the vicinity of the surface, is reported, which is obtained from crystallographic and optical studies of FIELO-GaNO. We have reported that the unique dislocation behavior of FIELO-GaNO causes the tilting of $\alpha$ axis in the overgrown regions. By using scanning reflection electron microscopy (SREM), the dependence of the tilt angle on the thickness of FIELO-GaNO was investigated. SREM images were obtained by recording the change of special reflection spot intensity. On a 51um-thick FIELO-GaNO, the clear stripe contrast reflecting the tilt on the mask region was observed, while the contract was found to almost disappeared on a 100um-thick FIELO-GaNO. This indicates that the tilt angle of the overgrown regions was recovered to less than 0.05° in the thick sample. The crystal quality of FIELO-GaNO was evaluated by x-ray rocking curve measurements. (0002) and (1010) diffraction peaks were used. We indicate that these peaks should be used together with the decrease of the dislocation density. The FWHM of (0002) diffraction peaks and (1010) diffraction peaks for samples having the dislocation density of the order of 10$^4$ cm$^{-2}$ was 94-130 arcsec and 138-180 arcsec, respectively. Finally, the optical quality of FIELO-GaNO was evaluated by photoluminescence (PL) decay time. The decay time for FIELO-GaNO was much longer than those for conventional MOVPE-grown GaNO and the longest decay time was 1.3 ns. These results indicate that the use of FIELO-GaNO substrate is promising for the fabrication of high-performance LDs.

4:00 P.M.  G5.7

HETEROPTAXY AND CHARACTERIZATION OF LOW-DISLOCATION-DENSITY GaN SINGLE CRYSTAL ON PERIODICALLY GROOVED SUBSTRATES: T. Deschprohm, M. Yano, R. Nakamura, S. Suno, S. Yoshiduki, H. Amano, I. Akasaki, Hiroshima Research Center, Mitsubishi, University, Dept of Electronic Engineering, Meijo University, Dept of Materials Science and Engineering, Meijo University.


4:15 P.M.  G5.8

DIFFERENCES IN STRESS RELEASE BETWEEN MBE AND
MOVPE GROWN AlGaN SINGLE LAYERS AND SUPERLATTICES. S. Einfeldt, M. Donnelseg, T. Böttcher, H. Heinke, D. Hering, Institute of Solid State Physics, University of Tübingen, 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 of the tensile stress is found to start via crack nucleation when a 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 behavior of MOVPE layers roughly fits to Griffiths concept of balancing the released strain energy and the introduced surface energy of the 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 expected to discuss different relaxation efficiencies of cracks in MBE and MOVPE films [1, J. S. Heard et al. Appl. Phys. Lett. 76, 1534 (2000).

4:30 P.M. G5.9


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 AlGaN, GaN heterostructures show an inherently strong spontaneous polarization oriented along the hexagonal c-axis as well as strain induced piezoelectric polarization. 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 AlGaN 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 AlGaN/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 AlGaN/GaN 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 AlGaN/GaN films. Both SE as well as room temperature CL of the AlGaN/GaN epilayer show a linear increase of the band gap energy similar to the observations made on cubic AlGaN/GaN 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 150 meV. In normally excited cubic 10% AlGaN (0.25 mm) multi-quantum well (MQW) structure has been realized. Room temperature and low temperature cathodo-luminescence clearly demonstrates strong radiative recombination due to quasiturn states in the GaN well layer at a photon energy of 3.3 eV.

g4:45 P.M. G5.10

GROWTH AND STRUCTURE OF GaN/C-PLANE SAPPHIRE WITH A NEW EPITAXIAL RELATIONSHIP. E.V. Kuznetsova, P.R. Twemer, D.R. Clarke, Materials Department, University of California, Santa Barbara, CA.

The standard growth of GaN on sapphire results in an epitaxial relationship of (0001)_{GaN} || (0001)_{sapphire}, (1102)_{GaN} || (1102)_{sapphire}, the twin relation 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} || (0001)_{sapphire}, (1102)_{GaN} || (1102)_{sapphire} with the twin relation occurring independent of orientation. This relationship corresponds to a rotation from the standard orientation of ± 19.4° around the c-axis. These rotated GaN films are of similar structural and morphological quality to standard films, with a rocking curve broadening of no more than 325 arcsec as measured both off and on-axis. Room-temperature Raman piezoelectricity 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 internal stress and structural and electronic properties of films with this alternate epitaxy are examined, and an examination in terms of a coincident lattice modeling 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

DEPARTMENT RELATED OPTICAL PROPERTIES OF UNDOPED N-TYPE GaN. S.J. Chang1, Q.H. Chu1, Y.S. Kim1, C.-H. Hong2, H.J. Lee3, M.S. Jeong1,1, J.O. White2, and E.-K. Suh1,2

1 Semiconductor Physics Research Center and Department of Semiconductor Science and Technology, Chonbuk National University, Chonju, KOREA, 2Frederick 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), photoluminescence (PL), and persistent photoluminescence (PL) measurements. PL and PPL results manifest a strong correlation in properties related to deep level samples which emit the YL exhibit a broad peak at 1.9 eV due to the photolumination of deep levels as well as the persistent photoluminescence effect, whereas samples with no YL have no peak in the forbidden gap and no PPL at any photon energy, suggesting that they have a common origin of deep level defects. Furthermore, two types of PPL behavior were observed depending on the sample thickness: typical stretched exponential decay in relatively thin samples, and photolumination-decaying and negative photon current followed by a reduction of the dark current in thin samples. From the temporal behavior of the UPC, the anomalous PPL phenomenon is attributed to the photoluminated metastable electron traps in a highly doped layer formed near the GaN buffer interface on a 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 MOVPE UNDER As2 AND As4. Andrew J. Winer, Ian Harrison, University of Nottingham, School of Electrical and Electronic Engineering, Nottingham, UNITED KINGDOM; Carl S. Davis, Sergei V. Novikov, Tim 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-molecular beam epitaxy under various As2 and As4 fluxes. The As has several effects on the luminescence properties of GaN. The intensity of the interband 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 2.46 eV, 2.86 eV and 2.9 eV. The positions of these peaks depend on the As flux. (These are not caused by interferences fringes). The variation of the intensity of cubic and the blue emission have different dependences with As flux. For the case of the blue emission, the power dependency (Flux)3/2, this is 0.74 and 0.49 for As2 and As4 respectively. The cubic case has power dependencies of 0.53 and 0.37 for growth under As2 and As4. From thermodynamic arguments the As surface concentration will have a power dependence on the flux. For As2 this will be 0.6 and 0.25 for As4. Therefore, these results provide evidence for the involvement of cubic GaN in the formation of GaN.
both its fundamental properties and its potential for 1.3 μm optoelectronic device applications. However, the incorporation of GaNAs in GaAs epilayers has been demonstrated to degrade the properties of the resulting (PL) devices. 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 described in detail. Two samples were grown by gas source molecular beam epitaxy on semi-insulating 3 μm GaAs (100) substrates: a 7 nm Ga_{0.7}In_{0.3}As/GaAs single quantum well (SQW) and a 7 nm Ga_{0.7}In_{0.3}As/GaAs single quantum well (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 low-lying transitions and that of the composite 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_f-H_e energy. This phenomenon indicates an inverted Stark-like dependence of the PL peak energy with temperature. The study of the RTA effects on the PL properties shows that the change in PL localization effects induced by nitrogen decrease with increasing RTA time: (ii) the PL-inhibited 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 BRUTE ePlan program, Contract No. BRPL-CT98-6721, Project No. BE95-4947.


We performed a comparative study of the optical properties of highly excited (11)GaAs epilayers and heterostructures grown by two different techniques: hydride vapor phase epitaxy (HVPE) and molecular pulse deposition at low pressure (MOCDV). We successfully achieved efficient low-threshold stimulated emission (SE) in HVPE-grown GaN epilayers and GaN/GaInN 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 MOCDV-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. This attribute the phenomenon to a higher density of non-radiative recombination channels in HVPE-grown structures in comparison to MOCDV-grown structures. The effects of GaInN confinement layers on the emission energy of the InGaN-active region structures have been thoroughly investigated. To our knowledge, this study represents the first demonstration of SE in HVPE-grown (11)GaInN heterostructures.

G6.5 WHITE LIGHT EMISSION FROM ELECTROLUMINESCENT DEVICES USING AN AMORPHOUS ALN MIXED DOPANT THIN-FILM PHOTOPHosphor. A.L. Martin, L. M. Calkins, M.E. Kerses, T.C. Spalding, P.R. Van Patten, Condensed Matter & Surface Science Program, Ohio University, Clippinger Laboratories, Athens, OH.

AN: Cu, Mn, Tb films, ~200 nm thick, were grown on p-doped silicon (111) substrates using RF magnetron sputtering in a nitrogen atmosphere. SEM, IR reflectance 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 AN thin-films indicate that the emission spectrum from Cu emitted blue at ~475 nm, Mn emitted red at ~675 nm, and Tb emitted blue at ~500 nm. The emission spectrum from Cu, Mn, and Tb doped AN thin-films illustrated a blend peak centered at ~530 nm. The relative amount of the blue, green, and red emissions were adjusted to yield the best white light emitter. An alternating-current thin-film electroluminescent (AC/TEPL) 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 ELECTROLUMINESCENT DEVICES FROM AMORPHOUS ALN, Mn, Cu, AND Cu FILMS. Meghan L. Caldwell, A.L. Martin, C.M. Spalding, M.E. Kerses, H.H. Richardson, P.R. Van Patten, 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 matrix. Wide-band gap III-V semiconductors are known to have many advantages over other III-V or smaller band gap semiconductors because of their superior electrical, thermal, and chemical properties as well as their resistance to ultraviolet damage. Most of this area has been concentrated on crystalline and polycrystalline GaN but recently visible emission has been reported from amorphous III nitride materials doped with Er, Pr, Tb, and Tm. AlN has a wide band gap than GaN but is not doped because the AlN phosphor material has been used in an alternating current thin film electroluminescent device. We have also reported visible luminescence from III nitrides polycrystalline devices previously described. The luminescence from Mn doped amorphous AlN. The luminescence has a peak maximum at 600 nm compared to 600 nm in crystalline AlN. We have extended these results to other transition metal dopants: Cu and Cu. Copper gives extremely strong broad band luminescence peaked in the near infrared at 1000-1200 nm when co-doped with Mn and Tb. The lower luminescence yield of Cu relative to Tb 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. Cu 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 EFFECTS IN GaN GROWN BY MOCVD. C. M. PHELPS EPITAXY. M.A. Richardson, M.H. Zhong, J. Cui, F. Yuan, and H. Morikoe, Virginia Commonwealth University, Richmond, VA; P. Visconti, Virginia Commonwealth University, Richmond, VA; and Italo per lo Studio di Novi Materiali per l’Elettronica, CNR, Lecco, 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 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-hole coupling. The energy of the local phonon mode and the Huang-Rhys factors 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 3.0-3.4 eV. These peaks are not extremely sensitive to excitation power and 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 InGaAs QUATERNARY ALLOYS. J-LI, K.B. Nam, K. Ken, J.Y. Lin, and H.X. Jiang, Department of Physics, Kansas State University, Manhattan, KS.

InAlxGa1-xN quaternary alloys of different In- and Al-concentrations 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 x-ray system (EDS), scanning electron microscopy (SEM) and atomic force microscopy (AFM) measurements. The growth condition dependence (temperature, pressure, metallicorganic sources and carrier gases follow ratio, 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 optical transient and quantum energy measurements of these InAlxGa1-xN quaternary alloys. It was found from XRD, RBS, and TRPL results that InAlxGa1-xN quaternary alloys that are lattice-matched to GaN (y = 4.7 e) have the highest electrical and optical qualities. The optical absorption processes in these InAlxGa1-xN 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 InAlGaInN quaternary alloy. We observed a similar behavior in AlInGaInN and AlGaN ternary alloys, and GaN epilayers. We found that the optical growth conditions as well as the electrical and optical properties of the InAlGaInN quaternary alloys are more closely correlated with those of the GaN alloy system than with the AlGaN alloy system. Heterostructures and quantum wells of GaN/InAlGaInN and InAlGaInN/AlGaN have also been fabricated and studied. Potential applications of the lattice-matched GaN/InAlGaInN and InAlGaInN/AlGaN heterostructures have been discussed. 


Blue and green GaN-based LEDs are commercially available for several years now. Usually they are grown on sapphire or Si substrates. Compared to Si these substrates have lower lattice and thermal mismatch to GaN and lower heat capacity, which might influence the behavior in the case of sapphire and much higher price especially in the case of Si 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 InGa/GaN LEDs were already reported two years ago but only little has been published since then. We present a study of electrically pumped InGa/GaN green light emitters on Si. The samples were grown by MOVCD 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.

6.12 PHOTOLUMINESCENCE AND CATHODOLUMINESCENCE INVESTIGATIONS OF GaN/AlGaN HETEROJUNCTIONS. S. E. G. 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. Turov, Ioffe Institute, St. Petersburg, RUSSIA.

We have examined multiple quantum well (MQW) 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 quantum well emission lines, as well as in the reduction of the oscillator strength of the transitions and their photoluminescence 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 quantum well 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 cathodoluminescence spectra taken at increasing beam current provide an insight into depth-dependent properties of the examined structures. The spectra show an unexpectedly small contribution from the substrate emission. Theoretical estimation 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 behavior of primary and secondary electrons in the specimen. Such strong influence has not been reported earlier.

6.13 INFLUENCE OF DIELECTRIC FUNCTION OF AlN/InN DETERMINED BY SPECTROSCOPIC ELLIPSOmetry. A. Knieš, M. Schubler, B. Rheinlander, J. Off, F. Scholz, C. M. Herzig, University of Leipzig, Dept. of Semiconductor Physics, Leipzig, GERMANY; B. M. F. University of Nebraska, Lincoln, NE; University of Stuttgart, Physikalisches Institut, Stuttgart, GERMANY; J.A. Woollam Co., Inc., Lincoln, NE.

Spectroscopic Ellipsometry (SE) from the mid-infrared (1500-3000 cm\(^{-1}\)) to the vacuum-ultraviolet (800-2000 eV) spectral range is used to determine the optical properties of Al\(_{1-x}\)In\(_x\)N thin films for indium contents 0.09 < x < 0.23. Al\(_{1-x}\)In\(_x\)N exhibits the largest band-gap variation of ternary group III nitride compounds and is interesting material for nitride lasers 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\(_x\)N have been reported so far. We use VUVSE and HRSE as novel techniques to study non-destructively phonon and band-gap
properties in thin AlInN films. Approximately 0.1 ... 
and GaN epilayers have been studied by using the 
and for growth-mechanism between Ga-polar and 
the cross-sectional cathodo-luminescence (CL) characterizat 
and for Ga-polar and N-polar GaN epilayers have been studied by using the 
high-resolution cross-sectional CL images can be taken under low 
the Ga-polar epilayers were grown on sapphire substrates by MOVPE, 
and the field emission scanning electron microscope (FE-SEM) so that high-resolution cross-sectional CL images can be taken under low 
and the trimethylaluminum (TMAI) pre-flaw just before the conventional two-step growth, and were confirmed with CAIC138. Distinct cross-sectional CL images of GaN 
and for the 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 
and/or growth-mechanism between Ga-polar and N-polar GaN epilayers has been studied by using the 
and the trimethylaluminum (TMAI) pre-flaw just before the conventional two-step growth, and were confirmed with CAIC138. Distinct cross-sectional CL images of GaN 
and/or growth-mechanism between Ga-polar and N-polar GaN epilayers has been studied by using the 
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and/or growth-mechanism between Ga-polar and N-polar GaN epilayers have been studied by using the
Engineering, Chiba University, Chiba, JAPAN; Kiyoshi Takeda,1 Department of Electronics and Information Science, Tokyo University of Science and Technology, Yamazaki, JAPAN.

In order to study the influence of Si doping in the barriers on the optical properties, time-resolved photoluminescence (TRPL) measurements were performed at temperature from 10K to room temperature. The samples were grown by LP-MOCVD on sapphire substrates with different barrier Si-doping levels in the barriers. From the PL decay time at different Si doping levels, the band tail width 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 nonradiative recombination on dislocations was found to cause a dramatic increase of decay time for lightly doped samples with the band tail width. It is found that 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 decreases with increasing Si doping in the barriers.

G6.20 CATHODOLUMINESCENCE AND MICRO-STRUCTURE OF POLYCRYSTALLINE GaN GROWN ON ZnO/Si. Tatsunori Araki, Hidetoshi Kageyama & Hiroshi Nozaki, Ritsumeikan Univ, Dept of Photonics, Shiga, JAPAN.

Interests have been attracted recently in optical property of polycrystalline GaN layer. We have demonstrated that the polycrystalline GaN layer grown by ECR-MBE on 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 oriented columnar structure. In this paper, we investigated the relationship between optical property and micro-structure of the polycrystalline GaN layers using CL, SEM and TEM. ZnO was prepared by magnetron sputtering deposition on Si (100) prior to growth. The ZnO was oriented polycrystalline consisting of many single crystal domains with various <110> orientations. A low temperature buffer layer of GaN was grown on the ZnO/Si substrate at 600°C for 15-20 min. Following this procedure, GaN layers were grown at 750°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 at 3.45 eV was observed from the GaN layer, which mainly showed columnar structure with a size of 100-200nm. 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 CL peak energy was found to be bluish-shifted. 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 grown on ZnO/Si. [1] H. Toshihata et al. Proceedings of 2nd ISHLED, Ts-P2-1 (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 understood. Besides 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. 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 periodicity on the quantum well peak, meaning that there was a constant well thickness. In one sample, the ratio th/w (th - barrier thickness, w - well thickness) is constant and in the other it differs for each well. PL spectra confirm these statements are presented. We present other optical studies, such as temperature, ultraviolet, and temperature-dependent. Electrical 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. Dalmaso, M. Leroux, M. Laugier and J. Massies, J. Appl. Phys. 86, 3714 (1999).


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 superlative 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. This work also has shown that both GaN and an Er doped amorphous AlN phosphor material has even been used in an ACTFEI 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 STUDY LOW-IMPURITY-RELATED PHOTOLUMINESCENCE IN HOMOEPIXTIAL GaN. V. Kirkulyt, A.R.A. Zoamer, 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 recognized that purity 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 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 epilayers 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 revealed an order of magnitude higher oxygen concentrations in the exact N-polar samples 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 intentionally doped substrate [2] into the epilayer. These results are consistent with the recently observed Mg contamination of Ga-polar homoepitaxial layers grown on similar single crystal substrates that were strongly compensated with Mg. I. V. Kirkulyt, et al., Appl. Phys. Lett. 76, 3155 (2000); 2. I. Gregory, et al., Mater. Res. Soc. Symp. Proc. 482, 15 (1998).

G6.24 Transferred to G5.4

G6.25 TIME AND SPATIALLY RESOLVED MICRO-PHOTO-LUMINESCENCE STUDIES OF GaN FILMS. G.E. Bonen, M.S. Uzoh, 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 hydrothermal strain associated with point defects in a 58 μm thick epitaxial lateral overgrown GaN layer with a limited microscope with a Sapphire solid immersion lens (SIL) was used to obtain a spatial resolution better than 200 μm, while maintaining temporal resolution: less than 65 ps and spectral resolution less than 0.6 Å. The sample was grown on a 5 μm GaN buffer deposited on c-plane Sapphire substrate by HVPE via a ZnO pretreatment. A 200 μm SiO2 film was deposited using pyrolytic reaction of silane and oxygen. AAr flowing consisting of 2 μm with linear window openings, repeating every 40 μm, was patterned...
using standard UV photolithographic techniques and CF₃ reactive ion etching. The ELO portion of the film was grown out of the openings and over the Si regions to an average thickness of 850 nm. The surface of each island exhibits an anisotropic curvature due to wing tilting of the α-case, yielding an average 4% thickness of ELO material than as-grown material in the mask openings. Micro-Raman spectroscopy shows no significant change in the bandgap of 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 hydrogen within the PL region with point defects. Indeed, low temperature micro-PL experiments show the presence of two different UV peaks, one at 3.483 eV and another at 3.331 eV. The intensity of the TE component of these peaks moves from coherently grown region to the ELO one. Detailed 3D 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 Er³⁺ PHOTOLUMINESCENCE AND PHOTOLUMINESCENCE EXCITATION SPECTROSCOPY IN IN-SITU DOPED GaN:Er AND ER-Implanted GaN.**

A. M. Mifsud, G. C. Popescu, and S. G. Bishop, University of Illinois at Urbana-Champaign, Dept of Electrical and Computer Engineering, Urbana, IL; D. S. Lee and Jj. E. Steckl, University of Cincinnati, NanoElectronics Laboratory, Cincinnati, OH; J. T. Seo and U. Hönninger, Hampton University, Dept of Physics, Hampton, VA.

Selective photoluminescence (PL) and photoluminescence excitation (PLE) spectroscopies have been carried out at 6K on the ~1540 nm 4I_{13/2}→4F_{5/2} emission of Er³⁺ in In-situ doped GaN:Er grown by molecular beam epitaxy (MBE). [The properties of in-situ doped GaN:Er 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 Er³⁺ centers and associated PL spectra. [2-4] PLE spectra of the Er implanted GaN showed that only one of the Er³⁺ centers could produce detectable emission when excited directly into the 4I_{13/2}→4F_{5/2} intra-4f shell transitions, while most of the other centers were excited by broad-band 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 implanted GaN are in environments that produce the PL spectrum that can be excited by 4f absorption [4,5]. Resonant pumping of Er³⁺ PL at the sharp line peaks of the 4I_{13/2}→4I_{15/2} 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. Significant differences in the Er³⁺ PL spectrum from in-situ doped GaN:Er are observed as a function of excitation wavelength within both the broadened tail of the 4f PL bands and broad, defect-related, bandgap PL bands, indicating that there are some significant variations in the Er³⁺ site configuration throughout the sample. Consistent with these observations, pumping by above-gap light simultaneously excites a variety of these Er³⁺ site configurations. In this manner, the observed ~1540 nm Er³⁺ PL spectrum is consistent with the broad band shape of the Er³⁺ PL spectrum and band gap absorption, although the bands are not as well resolved as the 1.15 µm Er³⁺ PL bands.

**G6.28**

**EFFECTS OF EXCITON-PHONON INTERACTION, DIELECTRIC MISMATCH AND ELECTRIC FIELDS ON THE EXCITON BINDING ENERGIES IN IONIC QUANTUM WELL HETEROSTRUCTURES.**

Guanglu Cui, 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 excitonic many-body response and the influence 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 potential for the exciton-phonon interaction by Pollmann and Böttner[2], and for the dielectric mismatch by Kumagai and Takahara[3], we have derived analytical expressions for the form factor which describes the effective e-h interaction accounting for the two effects simultaneously. The form factor is then used to calculate the exciton binding energies in quantum well structures in the presence of built-in electric fields. The results of our calculations can be summarized as follows: 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 energies strongly depends on the intensity of the internal electric fields. Different values for the spontaneous polarization have been suggested by theoretical[5] and experimental works[6], 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 e-h 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 our approach to include the effects of many-body interactions on the exciton binding energies will be also discussed. References: [1] T. Bernardini, V. Ferrari and D. Vanderbilt, Phys. Rev. Lett. 70, 5565 (1993); [2] D. Pollmann and H. Böttner, Phys. Rev. B 16, 4480 (1977) [3] M. Kumagai and T. Takahara, Phys. Rev. B 20, 12359 (1989) [4] R. Zheng and M. Matsuura, Phys. Rev. B 50, 10798 (1999) [5] M. Leroux et al., Phys. Rev. B 60, 1496 (1999).

**G6.29**

**OPTICAL AND ELECTRICAL STUDIES OF In₀.₃₋ₓAlₓN ALLOY FILMS GROWN ON (0001) SAPPHIRE. **

Y. P. Danylyuk, M.A. 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 In₀.₃₋ₓAlₓN alloy films (thickness ~150 nm) with increasing In concentration (~15% increments) were grown by Plasma Source Molecular Beam Epitaxy (PSMBE) on sapphire (0001) substrate. 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 In₀.₃₋ₓAlₓN 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 mobility are also presented.

**G6.30**

**OPTICAL SPECTROSCOPY OF GaN AND Al₂₀.₆₃GaN/GaN SUPERLATTICE DOPED WITH EUROPRIUM AND PRASÉDYMUM. **

H.J. Łoziński, W.M. Rychlewicz, School of EECS, and Condensed Matter & Surface Sciences Program, Ohio University, Athens, OH; J. Han, Sunnen Natural Labs, Albuquerque, NM; L.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 Al₁₀.₆₃Ga₈₉.₄N/GaN superlattice implanted with Eu³⁺ and Pr³⁺ ions. The characteristic emission lines corresponding to Eu³⁺ 4f⁶ 4P⁷/₄ and Pr³⁺ 4f⁷ 4I₁⁹/₂ shell transitions are resolved in spectral range from 800 to 1100 nm, and observed under photon (PL) and excitation (CL) excitations, over temperature range 8 - 380 K. The recorded
spectra show europium dominant transitions $^{2}D_{0} ightarrow 2F_{{2,3,4}}$, and praseodymium $^{3}P_{0} ightarrow 3F_{{2,3,4}}$, respectively. All observed transitions are weakly temperature dependent. The intensity of Eu$^{3+}$ emission from AlGaN/GaN superlattices annealed in N$_2$ is stronger (>50%) 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 compared with the Pr$^{3+}$ doped GaN epilayer. Generally, the excitation mechanisms and quenching processes will be discussed. The results indicate that rare earth doped GaN epilayers and Al$_{x}$Ga$_{1-x}$As/GaN superlattice are suitable as materials for various photonics devices.

**G6.31 SYNTHESIS, STRUCTURE, AND LUMINESCENCE OF A2B4C5 NITRIDES: Yevhenia Bondar, Lev Axelrod, Vladimir Davydov, Liow 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. The methods of synthesis of CaN$_2$, MgN$_2$, MgC$_2$, and MgN$_2$G$_2$ were developed, and X-ray diffraction analysis of them was carried out. It was found that CaN$_2$G$_2$ compound may be considered as the deformed wurzite structure with lattice parameters close to CaN$_2$. The A2B4C5 compounds extend the possibilities of controlling the substitution at permanent tetrahedral coordination of atoms. The following types of activation with luminescent dopants are possible in CaN$_2$G$_2$-crystal structure: isomorphic substitution of Ca atoms for Eu$^{2+}$; isomorphic substitution of Ge by Tl$^{4+}$; heterovalent substitution of Ca atoms by rare earth elements with formation of the defect Ca$_{1-x}$Ce$^{3+}$G$_{2}$-sublattice of type Ca$_{2}$Li$_{1}$Ge$_{2}$N$_{2}$CaN$_{2}$ and Mg$_{2}$Si$_{2}$N$_{2}$ nitrides with more complex structure give the possibility to introduce the activator into the cavities of cross-linked (Ca$_{2}$N$_{2}$) or Mg$_{2}$N$_{2}$ structure that is formed from the pairs of similar [Mg$_{4}$N$_{4}$] and [Si$_{4}$] tetrahedrons. Spectra of cathodoluminescence of phosphors based on Mn-, and Eu-doped nitrides A2B4C5 were investigated. The synthesized samples of CaN$_2$G$_{2}$, MgC$_{2}$, and MgN$_{2}$G$_{2}$ showed cathodoluminescence at 640 nm, and at 606 nm, respectively. Maximum of cathodoluminescence spectrum of Mg$_{2}$N$_{2}$-Mn is observed in the region of 640 nm, and Mg$_{2}$N$_{2}$-Eu phosphor showed cathodoluminescence at 630 nm. Intensities of ESH lines with g=2.0 and g=2.0 indicate on the introduction of Mn$^{2+}$ and Eu$^{2+}$ ions both in low-symmetry and high-symmetry positions of Mg$_{2}$N$_{2}$ lattice with isomorphic substitution of Mg$^{2+}$.

**G6.32 DEFECT-RELATED LUMINESCENCE IN AlGaN ALLOYS: Hideo Kohno, Henning Fricke, 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, Manhattan, 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, 3-dimensional electron gas-based field-effect transistors, heterojunctions for 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 AIN mole fractions of 0.24, 0.38, and 0.33. Both cathodoluminescence (CL) and photoluminescence (PL) was studied. The depth distribution of the accumulated layers was determined throughout the whole 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 3.6 eV using a 325-nm HeCd laser. Both CL and PL were studied as a function of temperature in the range between 30 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 observed 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-eplayer interface and becomes very weak for excitations closer below the surface in all samples. However, a 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. The results are discussed in terms of both stoichiometry-related and metal contamination-related defects.

**G6.33 DEVELOPMENT OF AIN BASED UV DETECTOR FOR SPACE APPLICATION: Rob CATTON, Feng Zhong, Changjie Huang, Jie Xu and Gregory W. Auner, Department of Electrical and Computer Engineering, Wayne State University, Detroit, MI.**

AIN is a great promising UV sensing material suitable for space application such as exo-atmospheric 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 AIN on Sapphire was developed. The space pixel has 588 x 588 UV imaging application. AIN epitaxial layers were grown by Plasma Source Molecular Beam Epitaxy (PSMBE). The quality of AIN thin films were characterized by in-situ 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 AIN thin films. In addition, etching process also improve the sensitivity of the detector array.

**G6.34 OPTICAL AND STRUCTURAL STUDY OF ION IMPLANTATION DAMAGE IN AlGaN: A. Savikhin, LSI Logic Corporation, Santa Clara, CA; N. Perikhi, University of North Carolina at Chapel Hill, Chapel Hill, NC; J. Hum and D. Peker, Metals and Ceramics Div., ORNL, Oak Ridge, TN.**

Doping of GaN with Mg during growth allows one to achieve hole concentrations of $10^{19}$-10$^{20}$ cm$^{-3}$ The alternative doping process is ion implantation. But this process is accompanied with generation of radiation defects and crystal's non-stochiometry. The post-implantation annealing, required for defects recovery and impurity activation is accompanied with GaN crystal sublimation. The goal 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 spectrophotometric ellipsometry (SE) and Rutherford backscattering spectroscopy (RBS). Quantitative correlation of both techniques was critically studied. X-ray GaN films grown on SiC with carrier concentration of 6$10^{18}$ cm$^{-3}$ were implanted with 1X10$^{15}$, 4X10$^{15}$, and 1X10$^{16}$ Mg ions. Implantation dose varied between 1X10$^{16}$ cm$^{-2}$ and 2X10$^{16}$ 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 the process of defects formation during Si ion implantation into GaN is more sensitive to the implant temperature compared to Mg ion implantation. (b) ion implantation at temperature about 1000-2500°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. Therefore, an estimate on the emission may varies with the temperature of the substrate during implantation.

**G6.35 OPTICAL PROPERTIES OF GaNd SINGLE LAYERS AND GaN/InAs/GaAs SUPERLATTICES STUDIED BY SPECTROSCOPIC ELLIPSOMETRY: Gunner Leibiger, Volker Gottschalk, Faculty of Chemistry and Mineralogy, University of Leipzig, Leipzig, GERMANY; Alexander Koeke, Faculty of Physics and Geociences, 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 GaN$_{1-x}$/In$_{x}$/GaAs [0 0 0 1] x < 3%] superlattices (SSL) with a single layers for photon energies from 0.75 eV to 4.5 eV and for wave numbers from 250 cm$^{-1}$ to 700 cm$^{-1}$. We use parametric models for data analysis to extract the optical constants of the GaN$_{1-x}$/In$_{x}$/GaAs SSL. The essential parameters are the thicknesses of the two SSL layers, the refractive index of the thin film layers, the transition probabilities, and the position of the interference maximum. The parameters $N_1$ and $N_2$, which are the refractive index of the GaN$_{1-x}$/In$_{x}$/GaAs SSL, and the position of the interference maximum, respectively, are determined by fitting the experimental data. The values of $N_1$ and $N_2$ are then used to calculate the optical constants of the GaN$_{1-x}$/In$_{x}$/GaAs SSL. The thicknesses of the two SSL layers are determined by fitting the experimental data. The values of $N_1$ and $N_2$ are then used to calculate the optical constants of the GaN$_{1-x}$/In$_{x}$/GaAs SSL. The thicknesses of the two SSL layers are determined by fitting the experimental data. The values of $N_1$ and $N_2$ are then used to calculate the optical constants of the GaN$_{1-x}$/In$_{x}$/GaAs SSL. The thicknesses of the two SSL layers are determined by fitting the experimental data.
of the GaN/GaAs/Si heterojunctions. The absence of free carriers in the InAs/GaAs/Si heterojunction goes along with an improved morphology, which is confirmed by a large effective piezoelectric constant and high temperature photoluminescence emission.

**G6.36**

**OPTICAL PROPERTIES OF A QUANTUM WELL OF A$_{1-x}$B$_x$ ALLOY SEMICONDUCTOR IN THE COHERENT POTENTIAL APPROXIMATION.** Yuasa Shinszuki, Hirotsugu Kid, Wakanaya University, Faculty of Systems Engineering, Wakanaya, JAPAN; Masahiro Watanabe, Yamaguch University, Faculty of Engineering, Ube, JAPAN.

We have theoretically studied optical properties of a quantum well (QW) in which GaAs is constructed by a slightly doped $(1-x)$ GaA$_{1-x}$B$_x$ alloy 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 $N_x$-x$N_y$,$N_z$ sites. A perfect confinement is assumed. Each site is occupied only by one A (B) atom with a probability 1-x (x). The system is characterized by the difference in the site energy, $\Delta E = E_A - E_B$, 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 $\Sigma(E)$ is assumed to be the same for all sites in the well, and is self-consistently determined with the average Greens function. The energy density states $E(x)$ is symmetrized with respect to $(x, 1-x)$ and $(E, E')$, while the optical absorption spectrum $\alpha(E)$ does not. For a slab $(\infty, \infty, N_z)$ and wire $(\infty, N_x, N_y)$, $\Sigma(E)$ is composed of $N_z$ or ($N_x$,$N_y$) subbands, each shown the two-dimensional quasi-two-dimensional singularity. When $x = 0.1$ is small, A (B) impurity-subband always appears at the lower (higher) energy side of each host-subband even for small A (B) impurity-host-subbands become wide and merge into the respective host-subband. The energy separations between subbands are found to be almost identical to $1/\text{N}_z$ ($1/\text{N}_x$,$\text{N}_y$) for the two-dimensional impurity-host separations are remarkable for thin well width ($3N_z$,$\text{N}_x$,$\text{N}_y$). We discuss the optical properties of In$_{0.1}$Ga$_{0.9}$N QW system with special attention to the localization. The effect of the off-diagonal dominance in $\Sigma$ and the optical absorption by the intersubband transition are also discussed.

**G6.37**

**POLARITY OF GaN THIN FILM PROBED BY X-RAY STANDING WAVE.** A. Kuzmirov, M.J. Bedzyk, Dept. of MS&E, Northwestern University, Material Science Division, Argonne National Laboratory; N. Pasek, H. Temkin, Electrical Engineering Dept., Texas Tech University, Lubbock, TX; V. Dmitriev, Yu. Mirolin, 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 Si. The film 300 nm thick had rather standard growth conditions (1% N$_2$ growth, 1013 Pa total pressure, 1200°C). The x-ray standing wave was generated inside the thin film using Bragg diffraction from the film [3]. The experiments were performed at the X1A beamline of the National Synchrotron Light Source, BNL. The angular dependence of GaN 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, as a function of angle of incidence, was used to determine the 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 MOVPE 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. DMR-9127343 [1] E.S. Hellman, MRS Internet J. Nitride Semicond. Res 3 (1998) 11; [2] Yu.V. Mikhlin et al., Diamond and Related Materials 6 (1997) 1532; [3] A. Kuzmirov et al., Solid State Commun 104 (1997) 347; [4] A. Kuzmirov et al., J. Appl. Phys. 84 (1998) 1709.
to a significantly higher defect density. The laser samples show strikingly different decay times: 340 ps for the unchopped, and more than 2000 ps for the chopped structures. The AIAS 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-dependent 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. Marcin Lisnik, and Ara Christian, 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 measured for optimization of the structure. Experimental data is fitted 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. AlInGaN/GaN and GaAIN/GaN material systems are shown to be the most suitable for highly reflective Bragg mirrors with minimized number of layers. LiF/Ga2O3 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. Hiroshi Hagiwara, Tatsuo Araki, Yoel M. Namiki, Ritsumeikan Univ, Dept of Photonics, Shiga, JAPAN.

Very strong luminescence has been observed from polycrystalline GaN grown on an amorphous silicon glass substrate, although the surface and SiC have been mainly used for the practical growth of GaN. This strong luminescence from polycrystalline GaN has attracted much attention in 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 of the relationship between microstructure and luminescence from polycrystalline GaN grown on silicon glass, by using scanning electron microscope (SEM) and cathodoluminescence (CL). Samples were grown on the silicon 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 domain 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 also observed. It was also revealed 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. However, 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 L214 (1998).

G6.44

A GENERALIZED ROOBSCHOECK-SCHOCKLEY RELATION FOR GaN-NITRIDES IN EAR-FROX EQUILIBRUM CONDITIONS. A.R. Vencenelles, R. Luzzi, Universidade Estadual de Campinas, Instituto de Fisica Gleb Wataghin, Campinas, Sao Paulo, BRAZIL; C.G. Rodrigues, Dept Fisica e Matematica, Universidade Catolica de Goias, Goiania, Goias, BRAZIL; V.N. Freire, Dept Fisica, Universidade Federal do Ceara, Fortaleza, Ceara, BRAZIL; J.A.P. da Costa, Dept. Fisica, 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 has been investigated, identifying 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]. When no non-equilibrium conditions exist far-from-equilibrium carrier dynamics for the description of the carriers dynamics in GaN. In this work, we consider the behavior of the absorption coefficient a(ε) and luminescence spectrum L(ε) in the steady state when III-nitrides compounds GaN, AlN and InN) are far-from-equilibrium conditions created by an electric field. Particularly, we analyze the higher frequencies part of their spectrum and derive a generalization of the Roobschloeck-Schockley relation a(ε) = f(ε)ε, the reason beyond the frequency dependent luminescence spectrum and absorption coefficient, for non-equilibrium conditions which are dependent of the electric field intensity E. We show that the carrier’s temperature within small error is proportional to [E²/κ + 4ε²]. 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.


G6.45

THE INFLUENCE OF DEFECTS AND PIEZOELECTRIC FIELDS ON QUANTUM WELL LUMINESCENCE IN InGaAs/GaN STRUCTURES. D. Cherns, S.J. Henley, A. Bewick, R.W. Haselton, and A. Ross, Physics Laboratory, University of Bristol, Bristol, UNITED KINGDOM.

High spatial resolution cathodoluminescence (CL) studies have been carried out on InGaAs/GaN quantum well (QW) structures in a field emission scanning electron microscope at temperatures down to 8K. Studies of a sample with a 30nm GaN cap and 1.5nm InGaAsQW were carried out at 4-6KV to maximise the QW luminescence. Spectrum taken from extended areas showed a progressive blue shift in the QW emission from around 460nm at low beam intensities to about 445nm in the beam intensity was increased. This blue shift is consistent with the QW band energy being 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 beam 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 compensated for 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. Olin, J. Kivioja, K. Saarinen, Laboratory of Physics, Helsinki University of Technology, FINLAND; A.E. Wickenden, D.D. Koleski, 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 layers with n=1.3(3.5)×10¹⁷ cm⁻³ were grown by MOVCD on sapphire substrate. The average grain size, determined by TEM analysis, increased from 0.2 μm to 2.5 μm with 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. Ga vacancies do not require the presence of dislocations. [1] J. Neugebauer and C.G. Van de Walle, Appl. Phys. Lett. 69, 503 (1996).

G6.47

THE ROLE OF FILM COALESCEANCE FOR DEFECT
FORMATION AND THERMALLY INDUCED STRAIN IN GaN EPILAYERS
Tim Böttcher, Sven Enkelmann, Stephan Fige, Marc Denschlag, Roman M"oller, Heiko Weidelt, 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 film 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 $5 \times 10^{13}$ cm$^{-2}$, whereas a smaller coalescence thickness results in reduced stress and increased defect density. A model describing the dependence on the coalescence layer thickness and hence 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 SGM GROUP III NITRIDE: I. Thermoelectric 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 Gr"{u}neisen-Sommerfeld compounds. This information together with the 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. Reeder, Mater. Res. Soc. Proc., Vol 482, 833(1998). 2. R.R. Reeder and K. Wang, J. Mater. Res., 15, 40(2000).

G6.50 PHASE SEPARATION IN MULTIPLE \text{ZnO}/C-Mg, Zn$_x$Mg$_{1-x}$O SUPERLATTICE HETEROSTRUCTURES OBSERVED VIA HIGH RESOLUTION TRANSMISSION ELECTRON MICROSCOPY: Alex Kreis, Shreyas Shekhara, Jay Narayan, North Carolina State Univ., Dept of Materials Science and Engineering, Raleigh, NC; Gerd Dauscher, Oak Ridge National Laboratory, Solid State Div, Oak Ridge, TN.

We have synthesized synthesized Zn$_x$Mg$_{1-x}$O alloys of wurtzite (0.0 \text{<} x \text{<} 0.34) and cubic (0 \text{<} x \text{<} 0.0.18) phases using nonequilibrium pulsed laser deposition method. High quality epitaxial films of Zn$_x$Mg$_{1-x}$O wurtzite structure have been grown on (0001) sapphire substrates, whereas, epitaxial cubic Zn$_x$Mg$_{1-x}$O films were grown on Si (110) 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 100 field-emission transmission electron microscope equipped with STEM and Gatan image filter, we can perform atomic structure determination, electron energy loss spectroscopy and imaging simultaneously. Such studies on the Zn$_x$Mg$_{1-x}$O superlattices provide direct evidence of phase-separation in the range of 3 nm, which may explain reduced recombination at defects via quantum confinement mechanisms have been used to explain high luminescence efficiency in GaN alloys. The experimental results are found to be consistent with model calculations.

G6.51 PREPARATION OF 30x30 mm$^2$ FREE-STANDING GaN WAFFER BY MECHANICAL LIFTOFF AND OPTICAL PROPERTIES IN THE BACKSIDE OF THE FREE GaN BY CATHODOLUMINESCENCE: Heo-Mok Kim, Tae-Woo Kang, Quantum Functional Materials Research Center, Dept of Materials Science and Engineering, Dongguk University, South Korea, SOUTHEAST 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 30x30 mm$^2$ wafer, was prepared 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 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 prepared free-standing GaN by cathodoluminescence.

G6.52 MASS TRANSPORT PROCESSES IN THE EPITAXIAL LATERAL OVERGROWTH OF GaN: T. McDevitt, C.C. Willson, M.E. Coltrin, J. Hae, 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 lineal growth rate. One commonly asked question is whether the lateral mass transport occurs at the stage when the growth rate enhancement is seen during ELO. We refer this question for mass transport above the masked regions and mass transport on and above the GaN epilayer. Deep trenches were etched into GaN wafers prior to the ELO growth, designed to introduce 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 the growth rate enhancement seen during ELO is caused by mass transport, such as diffusion, and not by the growth rate enhancement seen during ELO. This is further quantified by solving 3-D gas transport equations and using these to model experimental results.

G6.53 FLUX CONTROLLED LATERAL GROWTH OF GaN USING AMMONIA MBE: M.R. Heit, A.M. Dobirak, A. Parkhomykov, and P.J. 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 arrays were etched into 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 as shallow an angle as possible so that self-shadowing in the etched trenches modified the ammonia to Ga flux ratio on the side walls. Depending on the side position in a star, different Ga:ammonia flux ratios were obtained. Using description mass spectrometry 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 stars vs orientation in the star patterns measured. Lateral growth was observed, with lateral to vertical growth ratios from 5:1 to 2:1. No crystalline misorientation was observed. In this MBE case, the main feature controlling the growth rate was the ammonia flux ratio. Lateral growth was mainly observed on side walls on which there was no 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 p-type growth process.

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

A series of In$_{x}$Al$_{1-x}$N alloy films (thickness \textsim 150 nm) ranging in composition from AlN to InN were grown on sapphire substrates by Plasma Source Molecular Beam Epitaxy (PSMBE). Variation in In concentration (\textsim 15% increments) was achieved by...
increasing the rf source power. All alkyls, including the AlN film, were grown at the same conditions and low temperature (375°C) as required for GaN. A beam of high energy electron diffraction (RHEED) patterns show all films to be of the wurzite structure. All films exhibited single (0002) peak from X-ray diffraction (XRD) measurements confirming excellent crystalinity. Optical orientation of the wurzite 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 (STEM) 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.R. Pankovskiy, A.M. Dibabin, B. Benjaominson, B.E. Ishag, and F.I. Cohen, Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN, H. Han, C. Wullen, and J.Y. Tan, Sandia National Laboratories, Albuquerque, NM

Striking morphological dependencies are observed in the growth of GaN by ammonia molecular beam epitaxy (MBE) on a technically 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 andetching. Because GaN decomposes via a mechanism that deserts N, there is an activation barrier to decomposition. However, under excess ammonia conditions this activation should be reduced. In fact, we have observed the etching of MOCVD GaN under an ammonia flux. These templates are technically smooth showing step trains with 100 nm terraces. After annealing in ammonia at 780°C and 1.5 Torr pressures, some of these steps are still visible 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. Subsequent 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 ratio; 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 780°C. This represents a sensitive means to reveal dislocations and allows an understanding of the mechanism of rough growth.

G6.56
MOBILITY GROWTH OF GaN USING AMMONIA OR PLASMA-ACTIVATED MOLECULAR NITROGEN. A.V. Sampath, E. Hiepolous, A. Butachchery, T.D. Mostakes, 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 in the growth rates, the kinetic energies of the nucleation, surface reconstruction, polarity and optical 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 GaN 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 density 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 10^18 cm^-3 to 10^20 cm^-3. Similar results were obtained on either polarity of the films doped p-type with free hole concentration up to 10^20 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. 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 AIGaN ON SILICON WITH IN-SITU PYROMETRIC INTERFEROMETERY. Sergey A. Nikishin, Sebastien Francesoc, 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 AIGaN on silicon substrates. A pyrometer with a 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 sclusion coefficient of aluminum is equal to one, a detailed analysis of the interference effects yields the refractive index and the absorption coefficient of the layers on the index of reflection of a plane wave, which is used to derive the composition of the growing AlGaN film. The data provided by the 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
FINITE-VELOCITY CONSTANT METHOD FOR LATTICE DYNAMICS OF CUBIC InN. H.W. Leite Alves, J.L.A. Alves, DCDAT-FUNREI, Sao Joao do-Rei MG, BRAZIL, L.M. Scalfaro and J.R. Leite, DFMMF-USP, Sao Paulo SP, BRAZIL

Recently, there is a considerable interest on the physical properties of cubic InN; it is the most promising 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 context, using the Density Functional Theory (DFT) and the Potential Augmented Plane Wave (PAW) 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 included both hydrogenic and localized behavior. Our results show that the apparent divergence between the known experimental results is a consequence of hydrostatic effects on the data due to differences of the used dynamical methods.

G6.59
ANALYSIS OF ATOMIC STEPS ON BULK AIN CRYSTAL. FACETS’S. Nikolai Yakovlev, Carlos Rojo, Leo Schowalter, Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, NY.

Growth of bulk AIN single crystals is of significant interest to the III-nitride community for use as a substrate. The AIN 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<100> directions, which form triangles characteristic of the wurzite lattice. Scanning tunneling images were found to intersect this face (their density was observed to be < 10^10 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 stress of the dislocations or the density of kinks on the steps. Knowing the elastic constants and thermodinamic 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 in a proceeding step. We also identified (1120) facets. Their surface consists of goffers, which averaged 50 nm wide, and ran along the [1100] 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. Fink, M. A. Hasan, and M.J. Sawkaeta Jr, C.C. Cameron Applied Research Center & The Department of Electrical and Computer Engineering, University of North Carolina, Charlotte, NC. "Materials Research Laboratory, University of Illinois, Urbana CH.

AIN 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 GaN, which provides a tunable band gap for emission in the blue to red region. Moreover, integration of group II-III nitrides with Si would enable optical interconnects and high power device fabrication on Si. In this work, we have demonstrated growth of the crystallographic AlN 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°C. Each Al atom bonds to 3 Si atoms on the surface, which give rise to the wellknown Si[111]3x3 reconstrunction surface. The well ordered AlN covered Si[111]3x3 reconstruction surface was observed using a template to initiate epitaxial growth of AlN on Si. Without Al passivation, N
would react with the clean Si surface forming amorphous SiNx, 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 fired 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. AlN 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-crystal 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**

Rajender Singh, Carlos R. Eddy, Jr., Theodore M. Moustakas, Boston University, Dept. of Electrical & Computer Engineering, Boston, MA; Hoak & 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 ohmically. At moderate levels of rf bias power the extent of this degradation for nitride layers with higher doping levels (mid-10^{18} cm^{-3}) is far more severe than for nitride layers with lower doping levels.

**SESSION G7**
**ELECTRONIC TRANSPORT AND QUANTUM DOTS**

Chair: Bruno K. Meyer and Kentaro Onabe; Wednesday, Morning, November 28, 2000
Room 201 (Hyes)

**8:30 AM**
**G7.1**
**OBSERVATION OF THE QUANTUM-HALL EFFECT IN HIGH MOBILITY AlGaN/GaN HETEROSTRUCTURES GROWN BY MOLECULAR BEAM EPITAXY**

Michael M. Mabjed, Loren Pfeiffer, Kirk Baldwin, David Lang, Julian Hau 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 high mobility two-dimensional electron gas confined at the AlGaN/GaN interface grown by nitrogen plasma-assisted molecular beam epitaxy. The samples are grown by hydride vapor phase epitaxy. The electron mobility in this series of samples exceeds 50,000 cm^{2}/V•s at a carrier concentration of 2×10^{12} cm^{-2}. Capacitance-voltage profiling shows the unintentional doping level in the electron gas to be low (~10^{17} cm^{-3}) in the middle 10^{18} cm^{-2}. Magnetotransport studies at low temperature (∼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 3T. In addition to magnetotransport data, we discuss our investigation of the dependence of mobility on two-dimensional carrier concentration. Our data suggests that these exceptionally simple and small electron density Hall-VPE substrates can enjoy the interplay of disorder scattering and interface roughness present in the low temperature mobility in our low density (n < 1×10^{11} cm^{-2}) AlGaN/GaN heterostructures.

**8:45 AM**
**G7.2**
**HIGH ELECTRON MOBILITY IN FREE-STANDING GaN SUBSTRATES**


We also present the results of our efforts to grow and study epitaxial films of GaN on Si, grown in a hot-wall CVD reactor; and GaN layers grown selectively on free-standing GaN substrates. Free-standing GaN substrates were produced by wet-etching methods.

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 models: 1) a magnetic field dependent Hall effect model 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}/V•s 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 Si SUBSTRATES**


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, phonon, impurity, and dislocation scattering. The experimental results include the low field Hall measurements, cyclotron resonance measurements, and cryogenetic temperature Quantum Hall Effect studies as well as high-temperature characteristics of High Electron Mobility Transistors fabricated on all of these substrates. The room temperature high field measurements allow us to clearly separate contributions of the parallel conduction from 2DEG conduction in all investigated heterostructures. The Quantum Hall Effect measurements are performed in the magnetic fields up to 50 T and temperatures between 2K-80K. This high magnetic field in combination with very high mobilities (over 60,000 cm^{2}/V•s) in the simple 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**


Throughout much of the 1990s, state-of-the-art MOCVD-grown GaN and related materials were mostly better than those that could be achieved 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 will review the recent advances in MBE and demonstrate the viability of the technique. Currently, the nitrogen MBE growth is carried out in a dedicated arsenic-free system with the newest generation of plasma nitrogen sources. To avoid issues associated with misorientation on chemically disordered, lattice mismatched substrate [e.g., sapphire], all MBE growths are carried out on MOCD/GaN/sapphire 'templates'. We will show that the MBE structure, morphology, and physical properties critically depend on the ratio and substrate temperature. Through such observations, from the underlying MOCD layer, play a critical role in the morphology evolution. We find strong interplay between V/III ratio and dislocation-mediated morphologies. Optimal growth conditions are achieved for group III-rich (metal-rich) MBE systems. 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**

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 density bulk GaN substrates and 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. Experimental temperature dependent measurements are performed in a wide range of temperatures [50mK-300K]. Two cases are considered: (1) Low carrier density $\Psi_{2D}$ growth AlGaN/GaN heterostructures for cryogenic temperature application and Quantum Hall Effect studies. (2) High carrier density $\Delta_{CVD}$ grown AlGaN/GaN heterostructures for high power/temperature operation of HFET's. Our calculations show that at low temperatures, the electronic mobility is primarily limited by impurity scattering and scattering due to dislocation density; at high temperatures, the scattered is less important than polar optical scattering. The experimental results on low carrier density $\Psi_{2D}$ grown AlGaN/GaN heterostructures and high carrier density $\Delta_{CVD}$ grown AlGaN/GaN heterostructures for Heterostructure Field Effect Transistors (on bulk GaN, SiC, and sapphire substrates) confirm these conclusions.


Temperature-variable Hall and Submilim- de Haas effects have been used to study persistent photoconductivity in a high mobility unintentionally doped AlGaN/GaN heterostructure. The structure was grown by rf plasma-assisted molecular beam epitaxy on a sapphire substrate by metalorganic chemical vapor deposition. At liquid helium temperatures, the measured Hall mobility in this structure was close to 80,000 cm$^2$/V.s. A thin 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 of the ionized impurities, 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 shoulders on the de Haas oscillations were observed in the density 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; Jing Shi, J.H. Edgar, Korea Science University, Chemical Engineering Department, South Korea, RS.

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 case of GaNAs have been demonstrated to play a key role in the carrier relaxation. For GaN, AlN, and InN, phonon lifetimes and decay rates have been investigated by Tien 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 $\omega_1$(LO) and $\omega_2$(high) phonons on the single crystalline bulk AlN. The temperature dependence of the phonon lifetimes was investigated from 10K to 1273K. Our experimental results show that amongst the various possible decay channels, the $\omega_1$(LO) phonons of AlN decay primarily through two phonons of equal energy [Klemens model], most likely longitudinal-optical (LO) phonons. Therefore, there is a strong increase in the LO-to-LO decay channel on GaN, where the symmetric acoustic decay of the $\omega_1$(LO) phonon is not possible due to the rather large energy gap between the acoustic and optical phonon branches. For the $\omega_2$(high) phonon we find an asymmetric decay into a high-energy and a low-energy phonon. Phonon decay channels of the $\omega_2$(high) phonon include combinations of $\omega_2$(low) and acoustic phonons. Phonon lifetimes of the $\omega_1$(LO) phonon and the $\omega_2$(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. Ken Ishizawa,1,2,3, Yoshinori Akagi,1,2,3, Kuniaki Ito,1,2,3,1, Hideaki Takayama,1,2,3, Osaka Institute of Technology, Interdisciplinary Grad Sch. of Sci and Eng, Yokohama, JAPAN; 2RIKEN, Wako, JAPAN; 3JST-CREST, Wako, JAPAN.

For realization of the quantum logic gates such as 'qubit' or 'controlled NOT' using quantum dot devices, the control of the position, the size and the distance between the quantum dots are required. Coupled GaN quantum dots are good candidates for the realization of quantum 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 100nm in the electron beam exposure apparatus. After thermal cleaning at 600°C for 10min 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 dot channels of mean diameter is less than 40nm with 100nm period were controlled by changing growth conditions. It was found that the distance between near-diffusing dots can be also controlled with increasing tunneling length of less than 20A. 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 demonstration shows Coulomb blockade phenomena even at room temperature. The electrical transport properties of single electron transistors using the site-controlled quantum dots will also be discussed in the presentation.

11:30 AM G7.9 ELECTRIC FIELD MICROSCOPIC STUDY OF SURFACE STRUCTURE AND POLARIZATION EFFECTS IN GaN THIN FILMS. F. Yan, K.M. Jones, M.A. Haushak, J. Jui, M.H. Zhang, A. Sun, A. Buski and H. Morkoc, Virginia Commonwealth University, Richmond, VA; P. Visconti, Virginia Commonwealth University, Richmond, VA and INFN for the Studio di Nuovi Materiali per l'Elettronica, CNR, Lecce, ITALY; R. Mollor, MIT, Lincoln Laboratories, Lexington, MA.

Stress induced piezoelectric field in III-nitride semiconductors and spontaneous polarization induced electric field at the heterointerfaces along the $\alpha$-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 caused 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. Piezoelectric field gradient or the surface potential by electric force microscopy (EFM) with sub-micron lateral resolution, both a qualitative and a quantitative measure of piezoelectric charge distribution over the entire sample could be obtained. We have conducted an EFM study in a series of samples grown by different techniques and with different dopings. In $\Psi_{HR}$ grown samples, RHED 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 nascent and regrowth 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. Obtained images (XEFM) was used to image the electric field across the heterointerface 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 defects structures will be presented.

11:45 AM G7.10 SPATIALLY RESOLVED LUMINESCENCE INVESTIGATIONS ON GaN QUANTUM DOTS. M. Dieterich, J.C. Held, A. Hofmann, Department of Physics, Technical University Berlin, GERMANY.
Hennemann, J., Christen, M., Gmudelberg, GERMANY; I. Krestnikov, W.V. Landin, A.S. Uskov, N.N. Ledentsov, A.P. 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 raise quantum efficiency and low down current threshold is to take advantage of nano-structures. On this basis, we present experimental optical studies of quantum dot structures 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 square 8 µm x 8 µm mask of Ti and Pt. These masked samples were investigated using time and spatially resolved photoluminescence (PL) spectroscopy and cathodoluminescence (CL) in CL. In CL the GaN quantum dot structures were observed for the first time as a high quantum yield and quantum dot dot-like structure, respectively. The influence of local electric fields on the relaxation behavior of excitons and free carriers in these low-dimensional GaN nanostructures 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)

130 PM *G8.1 RESEARCH AND PROGRESS IN NITRIDE SEMICONDUCTORS AND THEIR PERSONAL HISTORY OF NITRIDE RESEARCH
Iwao 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 (TIs) 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 GaAs) opened up the successful path to the dramatic improvement of crystalline quality of nitrides. This dramatic improvement made it possible to 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 these devices. This buffer layer technique that has been widely recognized as the key to success. On the other hand, the nitrides grown on GaAs still contain 10^{10}~10^{13} cm^{-2} of dislocations. These dislocations do not affect severely the LED lifetime, but the obstacle for the high-performance LDs, TIs and UV detectors based on nitrides. Recently, great reductions in dislocation density have been achieved. In this paper, renaissance and progress in crystal growth and conductivity control of nitride semiconductors in the last two years are reviewed as the groundwork for recently developed high-performance devices.

My personal history of nitride research will also be introduced.

SESSION G9: CHARACTERIZATION AND BANDSTRUCTURE
Chairs: Chris G. Van de Walle and Bo A. Mosemmar
Thursday Morning, November 30, 2000
Room 210 (Hynes)

SESSION G10: CHARACTERIZATION AND BANDSTRUCTURE
Chairs: Chris G. Van de Walle and Bo A. Mosemmar
Thursday Morning, November 30, 2000
Room 210 (Hynes)

8:30 AM *G10.1 GROWTH AND CHARACTERIZATION OF THE GaN UNDERLAYER LAYER USED IN BLUE-VIOLET GaN-BASED LASER DIODES ON SAPPHIRE
Kenji Funato, Shigeaki Hashimoto, Katsumori Yamashita, Takao Miyajima, Kazuhisa Kobayashi, Semiconductors Company, CMC, Sony Corporation, Yokohama, JAPAN; Shigetaka Tanaka, Environmental and Analysis Tech, Dept., Sony Corporation, Tokyo, JAPAN; Tomomi Hino, Takaharu Azuma, Shiro Udade, Masa Rejda, Sony Shinbo Semiconductors Inc., Minagi, JAPAN.
Blue-violet laser diodes of a GaN-based material system were grown using metalorganic chemical vapor deposition. A separate confinement heterostructure laser was grown on the GaN substrate. We have achieved continuous-wave operation of the laser diode with a lifetime of more than 5,000 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 material, and 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 rate in each layer varied from 0.16 to 1.6 μm. 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 the lowered lattice pressure. Simultaneous 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 the model using transmission electron microscopy, the threading dislocation density was reduced by more than 10^6 cm^-2 in the layer grown under a pressure of 1.6 GPa. In the next stage, we used epitaxially laterally overgrown GaN layers as the underlying layer. The seed layer for epitaxial lateral overgrowth was grown under a pressure of 1.6 GPa. TEM images show that the threading dislocation density is less than 10^6 cm^-2 in the wing region, while it is 10^6 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. Chien G. M. G. H. M., S. N. G. H. M., K. C. W. B. L. W., and J. H. B. J. H., Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

Interband semiconductor quantum cascade lasers have so far been demonstrated in the InGaAs/AlAs/InP or GaAs/AlGaAs material systems, resulting in emission wavelength in the mid-infrared. To obtain shorter (< 3.5 μm) wavelengths, a material system with a higher conduction band offset between the active quantum well 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 Å 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 Å wide wells to a short as 1.55 μm for a 13 Å 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 also was carried from the structural and spectral width of the absorption of ~1.50 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. C. H. S., Chiba University, Institute of Applied Physics, Tsukuba, JAPAN. T. S. O. T. S., University of Electronics, and Computer Engineering, Tokyo, JAPAN. S. N. S., Nippon Chemical Industries Ltd., Department of Research and Development, Tokushima, JAPAN.

InGaN QW's 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 in addition to the strain induced by 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 QW's exhibit higher emission efficiency compared to GaN QW's, even at low excitation conditions although the oscillator strength should be reduced. In this contribution, results of static, modulated, and time-resolved measurements in InGaN QW structures [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 underlying. The interface roughness is not comparable to the binary materials. However, the PL emission 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 μm. However, small fluctuations of variation from 1.5% to 4% is also found. The bandgap energy difference between the two regions is estimated to be about 41-55 meV, taking the composition-dependent bandgap parameter (4.6 eV) into account. The value nearly agrees with the Starklike shift, and the strain-induced energy of the EL peaks. The piezoelectric field is calculated to be 230 kV/cm or 155 kV/cm depending on the piezoelectric constants used. Therefore, the hole and energy states are confined in the well. Weak localization of QW excitons occurs as a result of the large bandbowing parameter.

10:00 AM G9.4 EVIDENCE FOR 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 0.6 < x < 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 < 0.26 and decreasing them for x > 0.25. Chemical ordering along the [100] 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 THEORETICAL MODEL OF FREE EXCITON EMISION AND ABSORPTION IN WURTZITE GaN. A. V. Rodina, I. Physics Institute, Justus-Liebig University of Gießen, GERMANY. H. I. D. H., Technical University Berlin, GERMANY. B. K. Meyer, I. Physics Institute, Justus-Liebig University of Gießen, GERMANY.

We discuss 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 intrinsic 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 is evaluated using the theory with 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 are well separated from each other energy between the n=1 ground and n=2 excited state in GaN differ significantly from the values predicted by the effective mass theory. 2. The fine structure of the n=2 excited state of the A exciton results from the combined effects of the anisotropy, the interband interaction and the polar interaction with optical phonons. The 2S sublevel of this excited 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 the free holes in the A valence subband due to the interband interaction. 4. The polarization of an exciton is accounted for theoretically.

10:30 AM G9.6 SPONTANEOUS PSEUDOCOULOMBIC POLARIZATION IN II-VI NITRIDES ALLOYS: AN EXAMPLE OF NONVEGARD BEHAVIOR. Fabio Bernardini and Vincenzo Fiorentini, Istituto Nazionale per la Fisica delle Misure [INFN] and Dipartimento di Fisica, Universita di Cagliari, ITALY.

The knowledge of macroscopic polarization in II-VI nitrides alloys is a key ingredient in designing MQW structures of blue-green light emitting devices. So far polarization in alloys was estimated by linear interpolation or the values in InGaN and AlGaN. Supposing that polarization closely follows a Vegardlike 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 Body-force techniques, the spontaneous and piezoelectric polarization of AlGaN, InGaN and...
11:05 AM G9.7
UV RAMAN STUDY OF A1 (LO) AND E2 PHONONS IN InGaAl ALLOYS GROWN BY METAL-ORGANIC CHEMICAL VAPOR DEPOSITION ON SAPHIRE SUBSTRATES: Daniel Alfonso, Leslie Bergmann, Robert J. Nemchin, Dept of Physics, NC State University; Mitra Dutta, Michael A. Strascio, U.S. Army Research Office, Research Triangle Park, NC; C. A. Parker, S. M. Bednorz, Electrical and Computer Engineering, NC State University; N.A. El-Masry, Optical Science, UNC, Chapel Hill; Frédéric Weis, University of Liège, Belgium.

We report on UV Raman spectroscopy of In$_x$Ga$_{1-x}$Al$_y$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 695°C and 700°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 544.1 nm line of the frequency doubled Ar^+ 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 can yield ambiguous data, due to volume scattering by InN 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 photoemission. Investigation of the LO phonon-phonon interaction via the observed ratio of the A1(LO) and E2 modes suggests a surface depletion layer. Also, evidence regarding the presence of compositional inhomogeneities and spindled decomposition in InGaN thin films is presented. The mode behavior of the A1(LO) and E2 phonons was also investigated.

We have found compelling evidence for one-mode behavior for the A1(LO) phonon mode, while our data is suggestive of two-mode behavior for the E2 mode. These results are consistent with the previously found phonon behavior in AIGaN alloys.

11:10 AM G9.8
TEMPERATURE-DEPENDENT PHOTOELECTRIC INJECTION AND DEFECT RECOMBINATION IN GaN:PHOSPHORUS/InGaN QUANTUM WELLS WITH Si-DOPED BARRIERS: M.-Y. Ryu, Young Jun Yu, Phil Wen Yu, Kwangju Institute of Science & Technology, Dept of Information & Communications, Kwangju, SOUTH KOREA; Eun-Joo Shim, Joo In Lee, Sang Kyeu Yu, Korea Research Institute of Standards & Science, Optoelectronics Group, Taejon, SOUTH KOREA; Eon Soon Oh, Ok Hyun Nam, Chul Soo Sone, Young Jo Park, The III 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$_{0.10}$Ga$_{0.90}$N quantum wells (QW) by time-resolved photoluminescence (TRPL). Samples consisted of the following epitaxial structure: (i) a GaN layer; (ii) three-period QWs consisting of 45 Å undoped In$_{0.15}$Ga$_{0.85}$N wells and 100 Å Si-doped In$_{0.10}$Ga$_{0.90}$N barriers; (iii) a 400 Å thick undoped In$_{0.10}$Ga$_{0.90}$N capping layer. The lattice-matched QWs varied from 2 x 10$^{-8}$ to 1 x 10$^{-5}$ cm$^2$/V-s. We have employed two kinds of TRPL measurements. The one measured by time-correlated single photon counting (TCSPC) system. The excitation source is a picosecond mode-locked Ti:sapphire laser. For long-lived 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 decreases strongly on the Si-doping level in the InGaN barriers, decreasing from ~800 ns to ~200 ns as the doping level is increased from 2 x 10$^{-8}$ to 1 x 10$^{-5}$ cm$^2$/V-s. 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 component of a slower recombination component, a passivated layer was used. The slower decay time is decreased from several hundred ns to several ns with increasing Si-doping. The recombination lifetime becomes longer with decreasing emission energy, but 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 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.

11:15 AM G9.9
PROPAGATION OF EXCITON-POLARITON IN NITRIDE-BASED MULTIPLE QUANTUM WELL: Guillaume Maille, Alexey Ksokhin, LASMEA, University Blaise Pascal, Aubiere, CEDEX, FRANCE; Aldo Di Carlo, INFN-Dipartimento di Ingegneria Elettronica, Universita di Roma II, via Tor Vergata, a, 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. Two spectacular examples of this interplay are the propagation effects observed in the resonant Rayleigh scattering (RHS) 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 merging 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-polariton dispersion is produced by an order of magnitude as compared to the GaNAs-based quantum structures. On the other hand, the disorder in presently available GaN/AlGaN MQWs is much stronger than in GaN/AlGaN 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 semiclassical 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 RHS and pronounced VMN effect [3]. We predict polariton-induced oscillations in the time-resolved coherence spectra of GaN/AlGaN MQWs having a period of the order of hundreds of femtoseconds.

11:30 AM G9.10
TIME-RESOLVED PHOTOELECTRONIC MEASUREMENTS OF In$_{0.15}$Ga$_{0.85}$N/In$_{0.10}$Ga$_{0.90}$N QUANTUM WELLS WITH Si-DOPED BARRIERS: Y. Kido, Hiroshi Yokoyama, and T. Tsuchiya, Tokyo Institute of Technology, Tokyo, JAPAN; T. Sasa, T. Kondo, and T. Koyama, Nippon Telegraph and Telephone Public Corporation, Tokyo, JAPAN.

We have performed time-resolved photoemission spectroscopy (TRPES) measurements of disordered In$_{0.15}$Ga$_{0.85}$N/In$_{0.10}$Ga$_{0.90}$N quantum wells (QWs) with Si-doped barriers. The In$_{0.10}$Ga$_{0.90}$N capping layer was grown on a GaN substrate and the In$_{0.15}$Ga$_{0.85}$N QWs were grown on the Si-doped In$_{0.10}$Ga$_{0.90}$N barriers by metal-organic chemical vapor deposition. The capping layer thickness was varied from 2 x 10$^{-8}$ to 1 x 10$^{-5}$ cm$^2$/V-s. We have employed two kinds of TRPL measurements. The one measured by time-correlated single photon counting (TCSPC) system. The excitation source is a picosecond mode-locked Ti:sapphire laser. For long-lived 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 decreases strongly on the Si-doping level in the InGaN barriers, decreasing from ~800 ns to ~200 ns as the doping level is increased from 2 x 10$^{-8}$ to 1 x 10$^{-5}$ cm$^2$/V-s. 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 component of a slower recombination component, a passivated layer was used. The slower decay time is decreased from several hundred ns to several ns with increasing Si-doping. The recombination lifetime becomes longer with decreasing emission energy, but 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 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.

11:40 AM G9.11
LUMINESCENCE AND STRUCTURAL PROPERTIES OF InGaN EPILAYER, QUANTUM WELL AND QUANTUM DOT SAMPLES USING SYNCHROTRON EXCITATION: J. P. Kiss, P. M. White, Dept of Physics and Applied Physics, University of
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 wires), which form spontaneously during growth of InGaN/GaN MQW heterostructures. Quantum dots (QD) are expected to play an increasing role in the development of future optoelectronic and microelectronic devices, both in terms of performance and of cost. InGaN/GaN quantum dots are eventually expected to outperform InGaN/GaN quantum wires by ensuring lower carrier leakage and improved performance in high-power devices.

As applied to nitrides, self-assembly of quantum dots, of radius about 8 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 grown by metallicorganic vapor phase epitaxy (MOVPE), quantum dots 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 dots kindly provided by Dr Nicola 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 in situ/Ex situ diffraction source as a tunable white light nanofocused 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, quantum wire and quantum dot samples will be described and discussed.

SESSION G10: QUANTUM DOTS AND PHOTO DETECTORS
Chair: Volker Helle and Shigefumi F. Chichibu
Thursday Afternoon, November 30, 2000
Room 208 (Hyos)

1:30 PM *G10.1 RECOMBINATION DYNAMICS IN NITRIDE QUANTUM DOTS FOR COLORS RANGING FROM THE UV TO THE DARK ORANGE P. Ledezma, M. Gallier, A. Morel, T. Taboccos, A. Allegri, B. Gil and H. Michel, Groupe d'Etude des Semiconducteurs - CNRS, Université Montpellier II, FRANCE; N. Grandjean, D. Damilano and J. Masies, 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 using the Staackman growth transition. Halfwidths 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 models 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 large dots.

2:00 PM G10.2 OPTICAL PROPERTIES OF CUBIC GaN QUANTUM DOTS AND COMPARISON WITH HEXAGONAL ONES Julia Simon, Benoît Barilone, Fabien Serin, Christophe Lakowski, Gustavo Martinez Guerro, Régis André, Bruno Dusailly, Guy Feuillet, Le Si Dang, Guido Molin, Nikos T. Pekker, Henri Mariette, Département de Recherche Fondamentale sur la Matière Condensée, CEA Grenoble, FRANCE, and University J. Fourier, Grenoble, FRANCE.

Self-assembled cubic GaN quantum dots (QD) embedded in AlGaN/GaN have been grown by plasma-assisted molecular beam epitaxy on Si substrates. Transmission electron microscopy and atomic force microscopy reveal islands of mean height of 1.6 nm and mean diameter of 13 nm. Cathodoluminescence, time-integrated and time-resolved photoluminescence, and x-ray diffraction on these cubic (ZB) dots are compared with the ones obtained on hexagonal (WZ) self-assembled GaN 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 low ZB QDs, by contrast to the WZ QDs for which an energy lower than the bulk WZ GaN bandgap energy is observed 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 excitonic character of the nonradiative processes. (iii) The electric field at the ZB QDs is always lower than in the WZ structures and the decay times increase with decreasing QD size.

2:15 PM G10.3 FABRICATION AND CHARACTERIZATION OF MINI-DISPLAYS BASED ON NITRIDE BLUE/UV MICRO-LED ARRAYS H.-X. Jia, 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 InGaN+AlGaN/GaN single quantum well LED structures. These prototype mini-displays were fabricated by inductively coupled plasma (ICP) etching together with photolithography. Each micro-LED (pixel) was a 10 micron-diameter microdisk with a 50 micron spacing in between[1]. The performance characteristics of individual pixels including I-V and I-L characteristics, turn-on and turn off speeds, emission wavelength and line width, as well as a mini-display including uniformity of light emission intensity from different pixels, have been measured. The corresponding 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 solution 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.-Y. Li, J.Z. Li, J.-Y. Lin, and H.-X. Jia, Appl. Phys. Lett. 76, 631 (2000).

2:30 PM G10.4 AC OPERATION OF GaN/Er THIN FILM ELECTROLUMINESCENT MICRO-SEGMENT 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 excitonic luminescent centers. We have recently shown[3] that rare earth (RE)-doped GaN phosphors could provide full-color displays using both 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 based high field operation by current limiting the electrical breakdown of the GaN buffer. The green phosphor consisted of polycrystalline GaN:Er deposited on an amorphous dielectric layer consisting of one of the following: SiO2, Si3N4, Al2O3. The complete structure used an ITO transparent top electrode and a p-AlGaN 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 identical to that obtained previously with DC-type devices, with Er4+ 4f-4f emission lines at 488 and 550 nm. The luminescence 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/m2 at 65 Vp to 50 cd/m2 at 170 Vp. At an AC peak voltage of 170 V, the brightness increased linearly with frequency from 5 cd/m2 at 1 kHz to 50 cd/m2 at 10 kHz. A brightness of nearly 3000 cd/m2 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 insulator (Si3N4 or AlN insulators and GaN:RE phosphor) which can be insulated fabricated is particularly encouraging.

2:45 PM GI0.10

We report on a GaAs 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 photodetector exhibiting a large photocurrent gain of several thousands. In this regime, a typical detector response time is on the order of tens of microseconds, and the temperature of the dark current is larger than 150 K. Unlike other Schottky gates, 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 frequency response. Hence, choosing an appropriate gate bias establishes a trade-off between gain and speed. We also present a model that relates the photocurrent mode of operation to the hole trapping and to the corresponding shift in the threshold voltage.

3:30 PM #GI0.6
PERFORMANCE CHARACTERISTIC OF CW InGaN MULTIPLE QUANTUM WELL LASER DIODES. Michael Koeckelker, Xerox Palo Alto Research Center, Palo Alto, CA.

AlGaN:In laser diodes are currently undergoing rapid development and the commercial product based on this material has recently been introduced. The reduction of the dislocation density in the GaN material has been shown to be important factor to improve laser diode performance and lifetime. Although the benefits of low dislocation material have been clearly demonstrated by the rapid advances in the field, there is still very little known about how other laser properties, such as the distributed loss or internal quantum efficiency, are affected by the dislocation density in the material. In this paper we will compare the performance characteristics of AlGaN 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, under-critically threshold current densities as low as 5.9 kA/cm² 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 %/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 GI0.7
PHOTORESPONSIVITY OF ULTRAVIOLET DETECTORS BASED ON InAlGaN QUANTUM ALLOY ALLOYS. T.N. Oder, J. Li, J.Y. Lin, and H.H. Jiang, Department of Physics, Kansas State University, Manhattan, KS.

We describe the growth, fabrication and characterization of ultraviolet (UV) photodetectors based on InAlGaIn quantum alloy that are lattice-matched to GaN. InAlGaIn,Ga,Si quantum alloy of different In [x] and Al [y] compositions were grown on sapphire substrates by low pressure MOVCD. Films were characterized by different techniques including x-ray diffraction (XRD), Rutherford back scattering (RBS), secondary ion mass spectroscopy (SIMS), energy dispersive system (EDS), scanning electron microscopy (SEM), atomic force microscopy (AFM), Hall-effect and time-resolved photocurrent measurements. In [x] and Al [y] composition dependencies of optical and electrical properties of these quantum alloy have been studied systematically. The detectors consisted of 0.1 mm InAlGaIn,Ga,Si quantum alloy grown on 0.5 - 1.0 mm GaN epilayers. The characteristics of these UV detectors, including cut-off wavelength, responsivity, and device speed have been measured. With varying In and Al compositions, the cut-off wavelength of the InAlGaIn,Ga,Si detectors could be varied to the deep UV range. The most important and interesting results is that an InAlGaIn,Ga,Si quantum alloy excessed that of AlGaN on AlGaN of comparable cut-off wavelength by a factor of five. This makes the nitride quantum alloy very important material for solar-blind UV detectors. Application possibility to the deep UV range where AlGaN devices have problems with low quantum efficiency and cost was due in part to lattice mismatch with GaN. Advantages of InAlGaIn,Ga,Si quantum alloy over Al,Ga,N ternary alloys for UV detector applications will also be discussed.

4:15 PM GI0.8
SOLAR-BLIND AlGaN HETEROSTRUCTURE PHOTODIODES. J. D. Brown, J. Li, P. Schwall, J. Mathews and J. F. Schetinsky, 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 314 to 385 nm. This UV region is termed "solar-blind" because it 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,Ga,N/Ga,N-Si high-resistivity layer by MOVPE on a low temperature Ga,N layer on a polished sapphire substrate. On top of this base layer is a 0.2 μm undoped Al,Ga,N n-type active layer and a 0.5 μm p-type Al,Ga,N p-type top layer. Square means of area A = 4 × 10⁻⁴ cm² were obtained by reactive ion etching using BCl₃, Ti/Al and Ni/Al were used for n-type and p-type metal contacts, respectively. Techniques employed to maximize the flux of photogenerated current 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 280 to 500 nm with the devices illuminated by a UV lamp. OA Values were measured by calculating the difference between each sample. The ratio of OA indicates the maximum wavelength detected by the sample and is given in the table. The spectral responsivity threshold is very broad and is determined for each sample. The detector spectral sensitivity D Apostle was then calculated using a standard photodiode correction for a noise-limited detector. The solar-blind photodiode exhibited a very narrow UV spectral responsivity band peaking in the band with a full-width at half-maximum Responsivity R = 0.051 A/W and a full width at half maximum of Δλ = 1000 nm. The responsivity R = 0.051 A/W, the spectral half-width Δλ = 1000 nm. The spectral half-width of the solar-blind photodiode is appropriate for the fabrication of backside-illuminated photodiode arrays for use in solar-blind digital cameras. Initial 12x12 and 32x32 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 GI0.9

We are developing 256x256 solar-blind UV focal plane Arrays (FPAs) that capture photons across 0.28-0.36 μm. The photodiode technology is based on backilluminated 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 backilluminated AlGaN p-i-n device is a highly-doped n-type AlGaN window layer that serves as the common n-type contact to all the elements in the 256x256 array. The alloy composition of this layer determines the cutoff wavelength. The next layer is an unintentionally-doped p-type AlGaN absorber layer with a smaller band gap than the window layer, that forms an n-type 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 p-type absorber layer. The back-illuminated AlGaN p-i-n photodiode array has a number of advantages. It operates at zero-bias voltage, so 1/0 noise is not an issue. Because the absorber layer is nearly depleted at zero-bias voltage, quantum efficiencies are high; photocurrent collection depends on carrier diffusion which is an important consideration for a material such as AlGaN in which the diffusion lengths are quite short. Our backilluminated AlGaN p-i-n mesas photodiode array were fabricated from multilayer heterostructure AlGaN films grown by MOVPE onto 1 inch diameter c-plane double-sided-polished sapphire substrates. Mesas were etched by the Inductively Coupled Plasma (ICP) process to create minimal diffusion of the mesas at the surface. Using previously published AlGaN photodiodewere etched by dry etch methods. Both 256x256 arrays and variable area diagnostic arrays were fabricated side-by-side on the same wafer. Cutoff wavelengths for the photodiode reported range between 280 and 365 nm. This paper will describe the design, fabrication and performance of our 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 materials and processing characteristics. Our data will be compared to data previously reported for AlGaNP-p-n photodiodes. We will present performance data for 256x256 UV FPAs formed by hybridizing recently fabricated back-illuminated AlGaNP-p-n arrays to 256x256 silicon CMOS readout 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.

The work is being performed as part of the DARPA Solar Blind Detector Program, managed by Dr. Edgar J. Matson of the DARPA Microsystems Technology Office, under Office of Naval Research Contract N00014-95-C-0128, entitled “Solar Blind Detector Array.” The ONR Program Manager is Dr. Yoonsoo Park.

4:45 PM G10.10

UV DIGITAL CAMERA BASED ON 128x128 ARRAYS OF AlGaNP p-n PHOTODIODES. J.P. Schultz, J.D. Brown, J. Li, P. Srinivasan and J. Matthews, Department of Physics, North Carolina State University, Raleigh, NC; Thomas Nolte, Wei Yang, and Subrahmanya Krishnamurthy, Honeywell Technology Center, Plymouth, MN.

The first successful demonstration of UV focal plane array images based on two types of AlGaInN heterojunction p-n photodiodes that operate in the wavelength range from 380-365 nm is reported. The first diode structure consists of a 1.5 μm thick InGaN active layer followed by a 0.5 μm p-type GaN/AlGaN 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 AlGaN/AlGaN/AlGaN/Si layer, followed by a 0.2 μm undoped AlGaN top layer. These devices respond to UV radiation in the 380-320 nm wavelength region. Each of the 128x128 photodiode arrays consists of 16x128 mesa diodes. The mesa are 32 mm squares on a 38 mm pitch, corresponding to a fill factor of 72%. Photolithographically defined Ni was used to define the mesas, and Be33 react ion etching was used to etch the mesas down to the n-type AlGaN base layer. Ni/Au and Ti/Al metalfilations, 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 bump bonds were employed. The hybridized focal plane array 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 focused quartz lens for focusing the desired UV scene onto the AlGaInN FPA, together with an analog 500-μm Nyquist sampling rate prevents aliasing in the visible spectrum. The UV digital camera is capable of displaying real-time frame rates ranging from 15-30 frames per second or a sequence of images can be stored to computer as a digital images data set from which a selected frame or sequence of frames can be used to generate digital images. A variety of UV images of the 2633-365 nm region has been obtained using the nitride UV digital arrays. Single-frame visible-blind UV images of alpha-numerical, geometric, and astronomical scenes were displayed. Digital UV movies of pulsed xenon lamps, UV welding, and fire imagery were also presented. This work is being supported by grants from DARPA and ARO.

SESSION G11. POSTER SESSION

ELECTRONIC PROPERTIES AND TRANSPORT

Thursday, November 30, 2000

8:00 PM

Exhibition Hall D

G11.1

EVIDENCE OF POLARIZATION EFFECTS IN DOPED AlxGa1-xN/GaN SUPERLATTICES. Erik Waldron, E. Fred Schubert, John Graff, Boston University Photonics Center, Boston, MA; Andrei Osiansky, NZ Applied Technologies, Woburn, MA; Michael Murphy, William B. Smith, School of Electrical Engineering, Cornell University, Ithaca, NY.

Room temperature and low temperature photoluminescence studies of Mg doped AlxGa1-xN/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 related to 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 theoretical calculations for polarization field of 4 x 10^6 V/cm for room temperature Al0.1,Ga0.9N/GaN and 4 x 10^6 V/cm for room temperature Al0.2,Ga0.8N/GaN. At low temperatures the model yields 5 x 10^6 V/cm for Al0.1,Ga0.9N/GaN and 0.3 x 10^6 V/cm for Al0.2,Ga0.8N/GaN. The model also predicts strong excitation densities indicating screening of internal polarization fields by photo-generated free carriers.

G11.2

GROWTH AND INVESTIGATION OF GaN/AIN QUANTUM DOTS. H. Morkoc, M.A. Reshchikov, J. Cui, M.H. Zhang, F. Yun, M.I. Nihan, Virginia Commonwealth University, Richmond, VA; P. Vettiger, 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 layers by reactive and RF molecular beam epitaxy. The size distribution and quantum yields of the QDs have been estimated from the atomic force microscopy study. Very high quantum efficiency of photoluminescence (~90%) 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 blueshift of the QD related PL peak, whereas in the samples with larger dots redshifts up to 0.8 eV has been observed, which is related to strong polarization effects. We have observed a blueshift 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 size. The temperature-induced quenching of PL begins at high temperatures compared to the bulk GaN due to confinement of nonequilibrium carriers in the dots. 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 GaP-TYPE GaN: Shi K. Chen, Shuang C. Chang, Jyh R. Gong, Feng Chia Univ, Dept of Measurch Science, Taichung, REPUBLIC OF CHINA.

In this study, Ni/Au (5nm/5nm) was prepared by electron beam deposition to form the ohmic contact on GaP-type GaN with carrier concentrations of 2 Exp (17) per cubic centimeter. The deposited contact exhibited a specific contact resistance and transmission of 0.02 ohm-cm^2 and 41%, respectively. However, after a 500 degree Centigrade for 10 minutes they became 0.20 ohm-cm^2 and 78%, respectively. The improvement in contact resistance and optical transmission is considered to be closely related to the interdiffusion in the met ni/semiconductor interface and the formation of intermetallic phases GaN13 and Ga3Au7.

G11.4

AlGaN QUATERNARY CONDUCTING FILMS FOR SOLAR BLIND DETECTOR APPLICATIONS. Remzi Gaskin, Michael S. Shur, SET, Inc.; H. Srinivasan, G. Thanudaitis, V. Adve, Rasn, J.W. Yang, Univ South Carolina, Dept ECE.

We report on the growth and characterization of solar blind Al 0.37Ga0.63N quantum point conducting films for solar blind photodetector applications. The films were grown by MOVPE on GaN substrate. The addition of indium allows us to obtain z-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 10^17 cm^3 in the films with the Hall mobility of 6 cm^2/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 minor amounts of indium greatly improves materials quality and should allow us to obtain conducting quantum 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. Redmin, 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 in hexagonal semiconductors with wurtzite symmetry using the five band kp k model. The theoretical model of the interband transitions 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 find that anisotropy of the matrix elements between the lower 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 exponential dependence of the electron effective g-factor anisotropy in GaN samples with different strain situations. 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 wurtzite GaN are the major contributors 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 kp k model [1]. C. Hermann and C. Weisbuch, Phys. Rev. B 15, 829 (1977).

G1.16 IMPACT OF THE GROWTH POLAR DIRECTION ON THE EMITTER LIFETIME AND PERFORMANCE OF GaN LEDS GROWN BY METALORGANIC VAPOR PHASE EPITAXY. A. Setoguchi, A. Ueda, 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 II-VI semiconductors like GaAs, GaN-based devices are fabricated on the p-plane sapphire substrates along the polar axis of the wurtzite structure. Polarity of GaN films has been identified by several groups. However, correlation between the growth polarity and emission mechanisms of the grown film is still unclear at present. In this contribution, impact of the growth polarity 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 monochromatic slow positron annihilation technique are used to analyze impurity and vacancy defect profiles. The GaN film grown toward the Ga (0001) face (+polarity) exhibited clear excitonic features in its optical absorption and luminescence spectra up to room temperature. Conversely, the N (0001) face (-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 -p GaN due to increased impurity density and emission defect incorporation with MOCVD growth. The -p GaN contains large volume vacancy defects and donor impurities, which produce extended band tail states. Precise control of the growth polarity direction is necessary to obtain low defect density materials as well as specular surface.

G1.17 STRUCTURAL EVOLUTION OF Ni/Al CONTACT ON GaN(0001). C.C. Kim, K.J. Kim, J.L. Lee, and J.L.J. 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, Korea Advanced Institute of Science and Technology, Kwangju, KOREA; P. Batzill, Equipe Structure et Comportement Thermomecanique des Materiaux (CRISMAT UMR 6598 CNRS), Caen, FRANCE.

While GaN has attracted considerable interest in high-temperature and high-power applications, the structural behavior of metal contacts at elevated temperatures has not been clearly understood yet. Ni-Al system was known one of the most promising 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/Al contact system on GaN(0001) during annealing in N2, using synchrotron X-ray scattering and high-resolution transmission electron microscopy. Ni-Al metal layers evaporated at room temperature were grown epitaxially on GaN(0001) with the relationship of [111] // [111] and [1-10] // [0001] [1-20]. M=Al, Au. As the annealing temperature is increased up to 500°C, the Ni-Al metal layers 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 NiN, respectively. The two phases were grown epitaxially with the same crystallographic orientation as the metal cubic structure. We attributed the drastic deterioration of the ohmic property at high temperatures to the formation of these phases.

G1.18 POLARITY OF HEXAGONAL GaN GROWN ON GaAs [111]A AND [111]B SURFACES BY HVPE AND MOVPE. Osamu Takahashi, Motoki Nakamura, University of Tsukuba, Institute of Applied Physics, Tsukuba, JAPAN; Hidenosuke Tanaka, NIIT Cyber Space Laboratories, Musashino-ku, JAPAN; Ryutaro Suda, Nat. Inst. for Research in Inorganic Materials, Tsukuba, JAPAN; Takashi Suganuma and Masahide 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] GaN 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 investigation by CAICISS (Conical 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/I 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/I=50]. For MOVPE, about 10 nm GaN buffer layer was grown at 570°C [V/I=8000]. About 500 nm GaN buffer layer was grown at 950°C [V/I=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 NiAs polarity CAICISS spectrum, except for the growth on (111) B surface. 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. Therefore, MOVPE GaN grown on (111) B surfaces with the V/I ratio of 30 showed a typical Ga-polarity CAICISS spectrum, and the layer grown on (111) A with the V/I ratio of 4800 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/I ratio, but not necessarily by the substrate polarity itself.

G1.19 CHARACTERIZATION OF HETERO-INTERFACES BETWEEN VARIOUS SUBSTRATES AND NITRIDE SEMICONDUCTORS GROWN BY LASER MBE. Jitsuo Ohya, Hiroshi Fujikawa, Masaharu Oshima, The University of Tokyo, Department of Applied Chemistry, Tokyo, JAPAN; Masamune Sumiya, Electrical and Electronic Engineering, Shizuoka University, Shizuoka, JAPAN; Mitsuyasu Furukawa, Masamune Yoshimoto, Hideoki Imaein, Materials and Structures Laboratory, Tokyo Institute of Technology, Kanagawa, JAPAN.

Epitaxial growths of group III nitride semiconductors are usually carried out by growth of GaN on sapphire, SiC or Si substrates. However, when it comes to the formation of hetero-interfaces between substrates and nitride semiconductors because active nitrogen species and group III atoms arrive on the substrates simultaneously, the crystalline quality is a problem, especially for the 2-dimensional growths. In this presentation, we will discuss the initial stage of heteroepitaxial growth of nitride semiconductors by laser MBE on various substrates. We have grown GaN and AlN films on Si, sapphire, and LSAT substrates with a Keil Excimer Laser MBE apparatus. The laser light ablated the target with an energy density of 5 J/cm². During the growth at 750°C and 800°C, N₂ gas was introduced up to 1x10⁻⁵ torr for AlN and 5x10⁻⁵ 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 MOVCD chambers by the exposure to ammonia, which causes poor crystallinity of nitride films deposited on the substrates. The RHEED observations indicate that the initial stages of the AIN epitaxial growths on these substrates have revealed that most growths start 2-dimensionally, followed by the 3-dimensional island formation. The GaN CAICISS spectra have shown that the polarity of GaN films grown on LSAT is Ga polar. This result is in striking contrast to the c-growth in conventional plasma assisted MBE.

G1.10 ELECTRICAL AND STRUCTURAL CHARACTERISTICS OF Ti/Pt and Ni/Al-Ni/Au1:1 Grown on Schottky Diodes.

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Schottky diodes of Ti, Pd, and Ni/n-Al_{0.15}Ga_{0.85}N have been fabricated and the Schottky barrier heights were measured using LV, LVT, and C-V measurements. Fabricated diodes were annealed with different temperatures and times to understand the electrical and structural characteristics. Ammonia was used as a source for growing higher LV and C-V barrier heights when it compared with as-deposited Schottky diodes except high temperature annealed (450°C/10 min - 500°C/1 hr) Ti Schottky diodes. LV barrier height of Ti/n-Al_{0.15}Ga_{0.85}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 (1.03 eV) and C-V barrier height for both Pd (1.54 eV) and Ni (1.51 eV) Schottky diodes respectively. The decrease in barrier height 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_{0.15}Ga_{0.85}N and 500°C/1 hr for both Ti and Pd/n-Al_{0.15}Ga_{0.85}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_{0.15}Ga_{0.85}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.** Jun-Im Chyi, Chin Min Kan, Thee-En Nee, Chang-Cheng Chuo, Chin-Meng Lee, Department of Electrical Engineering, National Central University, Chung-Li, Taiwan, R.O. CHINA; Chin-Kun Peng, Procump Industry, Science-Based Industrial Park, Hsinchu, Taiwan, R.O. CHINA

III-nitride materials have been recognized as a key player in high-temperature electronics, lower voltage, and smaller size devices. Most of the previous work has focused on ALGaN/GaN high electron mobility transistors. 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-nm thick high temperature (1050°C) GaN buffer layer, a 15-nm thick InGaN channel layer, a 40-nm thick AlGaN/GaN Schottky layer, and a 10-nm thick GaN cap layer. The entire structure is undoped since spontaneous and piezoelectric polarizations induce 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/Al and Ni/Al gate stack processes 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 observed for NL and NL and 1.1 μm single-device transistors, respectively. As the temperature is increased to 300°C, the transconductance decreases to 50 μS/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, Kurni Physical-Technical Inst. of RAS, Kurni, RUSSIA; Takashi Inushita, 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 carrier - 500 μm main impurity - boron donors doping heavy boron. Two impurity states situated close to each other should have a new state with the energy different from the energy of impurity in an usual position. These states are ground states and in this sense differ from D_{app} states. It is shown that heavily boron-doped diamond have the hopping activation energy of 0.09 eV above the band edge and lightly boron-doped one had the activation energy of 0.37 eV. The density of the upper trap level is much smaller than that of the lower trap level. Compensation has a significant role to explain the conduction of the heavily boron-doped diamond. On the basis of the Fermi level calculation the model of 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 of heavily boron-doped diamond with temperature can be interpreted as the observation of the activation energy e12. In our case the observation of e12 is due to the transition from the valence-band conductivity to the hopping conductivity on the level u2 via the temperature change of the Fermi level. Thus e12 is a manifestation of the temperature change of the Fermi level in certain temperature range.

**G11.13**

**EMISSION CHARACTERISTICS OF GaN-BASED EL DEVICE WITH AC OPERATION.** Eiko Honda, Hidenori Kawai, Kohgiken Univ., Dept. of Electronic Engineering, Tokyo, JAPAN.

The GaN-based electroluminescence device (ELD) was fabricated using one GaN powders as an ELD. The electron emission spectrum of the GaN ELD under AC operation were observed at room temperature. The GaN layer was deposited using GaN powders and methanol at room temperature after the synthesis of the GaN powders. The results indicates that the GaN-based ELD will be one of the suitable light-emitting device for the flat display panels with low cost processes and wide area fabrications. The emission characteristics of GaN-based ELDs 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 were shifted toward high-energy side by increasing the frequency.

**G11.14**

**HIGH-TEMPERATURE ELECTRON TRANSPORT PROPERTIES IN AlGaN/GaN HETEROSTRUCTURE FIELD EFFECT TRANSISTORS.** Naruhiko Miyata, Toshihiko Saito, Ko Itano, Toshiro Tsubaki, Toshiaki Nishida, Nobu 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 channel is described as follows. The temperature dependent features of the optical (Po) phonon limited mobility. Moreover, the 2DEG density above R.T. has been found to be relatively large even at high 2DEG densities beyond the channel capacity. The AlGaN (Al=0.15), S-doped, 300 Å/GaN HFET samples, and S-doped GaN and AlGaN (Al=0.15) single-layer samples, were grown on Si substrates using AlN buffer layers by metalorganic chemical vapor deposition (MOVPE) at 300°C. As the mobility density of HFETs with a high 2DEG density (17 x 10^2 cm^-2) and R.T. exhibited mobility of 220 and 110 cm²/Vs at R.T. and 400°C, respectively; while bulk GaN (2x10^18 cm^-3) exhibited mobility of 210 cm²/Vs (R.T.) and 65 cm²/Vs (400°C). Although the mobility density decreased with increasing the temperature at around R.T., the decrease ratio in the mobility density above 300°C is small 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 attributed to the strong 2DEG confinement in HFET with high electron densities in the order of 10^16 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 (1x10^13 cm^-2) and the parallel conduction current. This is due to the relatively high mobility in the bulk AlGaN (115 cm²/Vs at R.T. for 1.3x10^17 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.** Je-Song Jung, Sang-Heon Hong, Dong-Jun Kim, Seong-Ju Park and Tae-Yeon Seong, Kwangju
We investigate the electrical and thermal stability of Pt-based Ohmic contacts to P-GaN:Mg. $N_x \approx 2.3 \times 10^{18} \ cm^{-3}$, which was two-step surface-treated using buffered oxide etch (BOE) and ammonium sulfide (NH₄HS) solution. The Pt (20/50/50 nm) and Pt/Ru/Au (20/20/20/50 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 showed that the as-deposited contacts produce a specific contact resistance in the range of 7.1 x 10⁻⁴ - 5.9 x 10⁻⁴ Ω cm². However, annealing of the contacts at 600°C results in a contact resistance in the range of 4.8 x 10⁻⁴ - 1.4 x 10⁻⁴ Ω cm². It should be stressed that for the Pt/Ru/Au-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 were studied in terms of thickness and surface treatments under various conditions. Measurements show that the transmittance is in the range of 87% - 93% at 400 - 470 nm. Post-deposition annealing treatment is performed to examine the thermal stability of the surface-treated contacts. To understand Ohmic mechanisms for the Pt-based contacts, electron transport mechanisms and interfacial reactions are investigated using X-ray photoluminescence spectroscopy, I-V measurement, Auger electron spectroscopy, Glancing X-ray diffraction, and transmission electron microscopy.

**G11.10**

**TECHNOLOGICAL IMPROVEMENTS IN THE ELECTRICAL AND OPTICAL PERFORMANCE OF InGa-N/GaN MULTI QUANTUM WELL LIGHT EMITTING DIODES BY TWO-STEP SURFACE TREATMENT.**


We investigate the effects of the 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. In the two-step surface treatment, the InGaN/GaN MQW layers were grown on S-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 structuring (first step) and before metal deposition (second step) using buffered oxide etch (BOE) solution. Pt/Ru and Pt/Al metallization schemes were used as p- and n-terminal electrodes, respectively. Performance of the two-step treated LEDs is compared with that of the conventionally treated LEDs. The EL 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 increases 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 strong relative to that of the conventionally treated LEDs. For the two-step treated LEDs, the EL intensity is uniform across the whole Pt/Ru transparent layer, while for the conventionally treated ones, randomly distributed dark spots are observed. The surface treatment dependence of the uniformity of EL intensity is explained in terms of surface state density and the alignment of metal grains. Interface characteristics are investigated using X-ray photoluminescence spectroscopy and time resolved EL measurement to investigate the effects of contact stability on the performance of LEDs.

**G11.17**


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 Auger electron spectroscopy (AES). It is observed that GaN films grown by MBE on HVPE GaN templates exhibited significant enhancement in bandgap transition at 3.4 eV compared to the original HVPE GaN templates. No detection of yellow luminescence (YL) is found on the MBE grown GaN and PL 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 HVPE films were grown on top of plasma-enhanced MBE GaN templates. Reflection high-energy electron diffraction (RHEED) and ion channeling measurements also revealed a better film quality can be obtained when using HVPE grown GaN as a template.

**G11.18**


InGaN has smaller effective mass and higher electron drift velocity than those of GaN. Therefore, InGaN is expected to be promising for the future electronic devices. InGaN, however, tends to grow three-dimensionally because of the lattice mismatch is large between the InGaN films and the substrate. In this paper, we demonstrate the surface morphology growth of InGaN using specimens grown on R-plane sapphire and electrical property by growing at 550°C on the buffer layer prepared by low temperature growth and consequent annealing. InGaN films were grown by RF-MBE. The substrate used in this study was (0001) sapphire. Prior to growth of InGaN, 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 hr with nitrogen flow rate of 1 scm and RF plasma power of 300 W. Following the nitridation process, InGaN buffer layers were grown at 300°C for 10 min. Then, the substrate temperature was raised up to 550°C, then InGaN films were grown again on the buffer layers thus prepared at 550°C for 1 hr. The bandgap equivalent pressure of the elemental In an the N;2 flow rate were 3.2 x 10⁻⁷ Torr and 2 sccm, respectively and kept constant through our experiment. Only RF power was varied between 230 W and 250 W. Thickness of the InGaN film grown for 1 hr was about 200 nm. From SEM observation, it was found that the surface morphology was improved by reducing RF power to 230 W. Many In droplets were appeared, however, on the surface of InGaN film. From Hall measurements, the InGaN film grown at 230 W was confirmed to have excellent electrical property with its electron mobility of 205 cm²/Vs at room temperature and carrier density of 3 x 10¹⁸ cm⁻³.

**G11.19**


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 across 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, the quantum well size dependence of the piezoelectric field. For the two-step treated LEDs, the EL intensity is uniform across the whole Pt/Ru transparent layer, while for the conventionally treated ones, randomly distributed dark spots are observed. The surface treatment dependence of the uniformity of EL intensity is explained in terms of surface state density and the alignment of metal grains. Interface characteristics are investigated using X-ray photoluminescence spectroscopy and time resolved EL measurement to investigate the effects of contact stability on the performance of LEDs.

**G11.20**

**MEASUREMENT OF POLARIZATION FIELDS AND FREE CARRIER SCREENING EFFECTS IN GaN/InGaN/GaN SINGLE QUANTUM WELL STRUCTURES BY ELECTRON HOLOGRAPHY.** J. C., M. R., N., F. A., 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 nitride materials is critical for understanding the optical and electronic properties of these devices. Electron holography provides us with the ability to profile the local internal potential at the monolayer 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 electronic potential across the GaN/InGaN (27 Å) 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 high as 30 MV/cm exists in the InGaN/GaN quantum hologram also reveals bend-bending over atomic spacing distance in the vicinity of two interfaces between GaN and InGaN. Simulations suggest free electrons at high-resolution electron holography 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
Elaine D. Halsen, Ching-Hui Chou,1 Stenkel Keller,2 Monica Hansen, Unmesh Mishra, Steve DenBaars, John Bowers1, Evelyn Hui1
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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 specific configuration and bond reconstruction, the air-semiconductor interface can be a source of non-radiative recombination. As the surface area to volume ratio increases, in smaller optical devices, non-radiative 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 in particular, and thus non-radiative recombination is an important consideration. Scaling effects have yet to be fully characterized in GaN. In this study, we use a quantum well (QW) probe to explore the size dependence of sidewall recombination in GaN. The structure had an InGaN/GaN QW capped with 150 Å GaN. Ridges of widths of approximately 2.3, 4, and 3 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/cm² for 15 minutes. Two different Cl₂ flows were used for these experiments: 2 scm and 5 scm. Depending on the Cl₂ flow, the etch depth was approximately 1500-2000 Å; therefore the 150 Å deep QW was exposed on the ridge sidewall. Room temperature PL measurements showed no observable reduction in PL intensity and thus no detectable changes in growth. These results show that even with 4 micron ridge width, sidewall recombination may indeed play a significant role in non-radiative recombination processes. Time-resolved photoluminescence (TRPL) carrier lifetime measurements were being taken to confirm this conclusion.

G11.22
HIGH MOBILITY TWO-DIMENSIONAL ELECTRON GASES IN AlGaN/GaN HETEROSTRUCTURES ON FREE-STANDING GaN QUAANTUM SUBSTRATES
C.R. Maksy, R. Dimitrov, A.P. Lima, O. Amohander, and M. Sturzmann, Walter Schottky Institute, Technical University of Munich, Garching, GERMANY.

Free-standing GaN quantum substrates produced by laser lift-off of thick HVPE GaN layers from sapphire we used to obtain high quality two-dimensional electron gases by epitaxial overgrowth with mBE and MOCVD. Homoeptaxial GaN layers on such quantum substrates exhibit a much lower dislocation density (2 x 10² cm⁻²) and much lower thermal strain compared to heteroepitaxial GaN layers grown on sapphire. Step-flow growth can readily be achieved by overgrowth with MOCVD, resulting in homoeptaxial layers with a rms surface roughness as low as 0.2 nm. X-ray diffraction patterns with a FWHM below 20 arcsec, and excitonic luminescence peaks below 500 meV, demonstrate that these epitaxial grown layers are readily produced by depositing, e.g., an AlGaN heterolayer onto a GaN substrate. The substrate in the spontaneous pyroelectric polarization on each side of the heterostructure together with the p-type GaN layer results in a significant interface charge. This, in turn, causes the appearance of a compensating 3D electron gas with high carrier densities and interesting applications for high-frequency, high-power devices. In the present case, homoeptaxial GaN epitaxially grown on mBE and MOCVD substrates was characterized with respect to their structural and electronic properties. Particular attention is paid to the correlation between structural and electrical properties of the samples. In addition, we have noticed a pronounced correlation between the size of the current and the maximum observed mobility. This suggests that lateral inhomogeneities 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
Min Yong Kim, Hyeong Joon Kim, School of Materials Science and Engineering, Seoul National University, KOREA;
Young-Jin Kim, Kyungpook University, KOREA; Cheolho Seo and Yong Jo Park, Samsung Advanced Institute of Technology, KOREA.

Gallium nitride and its solid solution with InN and AlInN have attracted attention because of their potential optoelectronic 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 development, 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 accurately 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 films with properties were investigated using SEM, TEM, Raman spectroscopy 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 damped and Rayleigh velocities, theoretical SAW velocities were simulated using numerical computations. We also calculated the film elastic constants from SAW propagation velocities in the layers. From the acoustic characteristics, Mg-doped GaN thin films showed the stiffening effects and the elastic constants and propagation loss are similar to those obtained for pure GaN thin films.
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. Andrews1,2, P.B. Doyel3, T.M. Pendry4, K. P. Lupo, Ioffe Institute, St. Petersburg, RUSSIA; 1Physics Department, Queen Mary and Westfield College, London, UNITED KINGDOM; 2Physics 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 spectrum and wave functions are calculated using a plane-wave expansion method and compared with a multi-band effective 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 were grown 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 internal confinement of the carriers. As a result, the effective lateral dot size becomes smaller than the real dot size, the electron and hole states are localized 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 different sized dots with and without dislocations. The size of the dot influences the energies and optical properties, but the presence of the dislocation line 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] and [2].


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 m²/cm² and to reduce the current density by 3-4 orders of magnitude as compared with conventional planar structures. To introduce GaN into the opal matrices we used heterogeneous chemical reactions of NH3 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 photocurrent measurements were studied with excitation by a KrF laser radiation. 5 ns pulses at 522 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 2900 A with U = 0.2 V]. The PC peak values are proportional to the square-root of pulse energy, which 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 photocconductivity (PPC). The current build-up during pumping with the 522 nm laser line is characterized by a fast, linear 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 (681) [1]


We report mesa-isolated Schottky barrier photodetectors fabricated on n-[Al]GaN. Single-element detectors and 32 x 32 array were constructed from nitride epilayers grown by gas source molecular beam epitaxy on Si[111]. Chlorine-based reactive ion etching was used to etch two-level masks. The devices were all fabricated through 100 µm transparent Schottky contacts on the upper mesa; ohmic contact on the lower mesa was made using standard Ti/Au/Al metallurgy. Silicon dioxide grown by plasma-enhanced chemical vapor deposition acted as an electrical isolation. The dark current of an 8.6 x 86 mm² single-element detector is ~ 2 10⁻⁴ A/cm² at ~2 V bias. Results of noise measurements and performance will also be presented.

G11.28  AIN SAW SENSORS USING EXCIMER LASER MICRO-MACHINING TECHNIQUES. Dang Zhang, Zhong Zhao, Chang Hua, W. E. Kimer, D. L. Revier, and K.P. Lupo, Ioffe Institute, St. Petersburg, RUSSIA. AIN is a promising piezoelectric material for Surface Acoustic Wave (SAW) transducers due to its high SAW velocities and electromechanical coupling coefficient. Epitaxial AIN 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 micro-machining techniques were utilized to fabricate microgrooves or microchannels on the surface of AIN SAW sensors to reduce the excess attenuation and improve the output signal. The effects of these micromachined channels on the performance of AIN SAW sensors will be presented.


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 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-voltage 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 in energy than in the conducting bulk film. These results are inconsistent with high density of electrons in the intrinsic conduction band. Rather, they point to the presence of a partially filled donor impurity band in 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. Surface-related effect is seen in several papers and is critical for probing the effect of defects/impurities on material physical properties.

G11.30  A HIGH RESISTIVITY GaN FORMED BY ION IMPLANTATION. Jun Kudo, Motokazu Yamaoka, Yuki Hashida, and Masanori Watarase, 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 into a K-doped epitaxial GaN layer, with 4 x 10¹⁷ cm⁻³ donor concentration and 0.6 µm thick, grown on the undoped GaN/Sapphire substrate. A line doping profile in the range of 10¹⁷, 10²⁰cm⁻³ was obtained at the depth of 0.2 - 0.3 µm from the surface by multistep implantation. After forming Ti/Au/Ni electrodes, the sample was annealed at 550 - 850°C for 1 min. The resistivity of as-implanted layers is 10¹⁵ - 10¹⁸ Ω·cm for those of 0.2 - 0.3 µm thick, and 10⁵ - 10⁶ 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 10⁵ Ω·cm after annealing at 850°C, which is consistent with a recent report by Kuznetsov et al. that GaN formed at 950 ± 150°C by hydride VPE, with Zn concentration of 2 x 10¹⁷ cm⁻², yielded the resistivity larger than 10⁻⁵ Ω·cm. The present result shows 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 recombination of intrinsic 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. Ruffennach-Clr, O. Bricot, N. Moreau-P. Calm, L. Aubertem, C. E. C. Gran, Grenoble, FRANCE.

AlGaN/GaN heterostructures have both a theoretical and practical interest due to their symmetry. 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 HEIM 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. In contrast, MOCVD grown samples exhibit lower electric fields. Since the electric field may be reduced to the gradient of polarization across the interface, one may think that MOCVD samples, grown at a high temperature suffer from a large interdiffusion in the AlGaN/GaN interface, 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 30 monolayers and an Al composition of 10%. The samples were studied by low temperature (5K) photoluminescence and reflectivity, X-ray reciprocal space mapping, and transmission electron microscopy. Narrow PL lines were obtained for the quantum wells, the contrast-shifted from the reflectivity structures, and their energy can be continuously thickened with 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 explains the reduction of the electric fields is observed.

G11.32

We have developed a self-aligned fabrication process for small emitter contact area (24μm²) GaN/AlGaN heterojunction bipolar transistor is described. The fabrication employs dielectric-spacer sidewalls, ICP dry etching and selected-area-growth of GaAs(C) on the base contact. The junction L-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 etch back comparison with the performance of large emitter area (2x50μm²) 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. Raman Golla, Raoul Schlaffer, Amy Rosebrook, Robert F. Davis, Zdzislaw Stober, 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 (100kV/cm), the electrons follow a Maxwell 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 carrier dynamics is associated with the energy 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/AIN AND SiC/ GaN POLAR INTERFACES. Morad Housse Lebzi, Pierre-Marc, Groupe D’Etude des Semiconductor, 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 crystalline directions of SiC on 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 undersaturated 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 pyroelectric and piezoelectric character of hexagonal SiC and wurtzite AlN and GaN. In these materials, the divergence of the microscopic 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 the formation energies 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/AIN [0001] heterostructures to lie in the range 0.7-1.7 eV, and 1.4-2.3 eV, respectively. Our studies show that SiC/AIN heterostructures are always of type I, whereas SiC/GaN heterostructures 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, G. Alexander Zandeler, 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 nitrogen devices. Recently, it has been suggested that electric fields caused by the pyro- and piezo-electric 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 electron structure of these interfaces, compare them 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 interlayer wave functions has been taken into account and the hole density has been calculated by integrating over the Irreducible Brillouin Zone. We find the 2DHG density to be mainly controlled by the polarization change 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 gatelayer heterostructure with a homogenous only Mg dopant AlGaN layer demonstrate that the 2D hole density can reach values up to 1.5x10¹⁰ cm⁻² for 30% Al concentration. In doped GaN/AlGaN superlattices, we find the 2DHG density to be quite low for short well end barrier widths, but to increase significantly for thicker layers. We predict a maximum hole sheet density of roughly 1.6x10¹⁰ cm⁻² for 40% Al/GaN 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 Bondin,
Electro- and photocoercivity 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 coercivity. The obtained experimental dependencies of coercivity of substrate temperature and nitrogen pressure on GaN films deposition indicate on nitrogen vacancies as the most probable donor-type defects in these films which determine their coercivity. Our results show that increasing of GaN films coercivity 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 thermodynamic 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 minimum of photocoercivity at 360-380 nm. Films sputtered at substrate temperatures higher than 900K showed the broadening of photocoercivity band with shift of maximum to 400-410 nm region. The reason could be, that at higher substrate temperature 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 addition to photoconductance bands in long-wavelength region of absorption edge and broadening of photocoercivity region.

G11.37
GAS SOURCE MOLECULAR BEAM EPITAXY OF HIGH QUALITY ALGaN Gₐ₅N (0 ≤ x ≤ 1) ON Si AND SAPPHIRE
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We report the results of epitaxial growth experiments of AlGaN_{x}N (0 ≤ x ≤ 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 AlGaN_{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 Si-N-Al interlayer between Si substrate and AlN layer, at 1130-1190 K, results in very rapid transition to two-dimensional (2D) growth mode of AlN. The resulting AlN layer is thermally released 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 AlGaN_{x}N we observe a systematic dependence of the surface morphology and the growth mechanism on composition x and buffer layer. In layers free of cracks, we find background electron concentration around (4·5)·10^{16} cm^{-3} and mobility (400±100) cm²/V·s for 2 μm GaN film thickness. A GaN_{x}N (0.2 ≤ x ≤ 0.6) the lowest electron concentration is around (2·3)·10^{16} cm²/V·s for the film thickness of 0.5-0.7 μm. PN junctions 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

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 c-axis (001) planes. The 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, but in the periodicity of two 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 with a new model of ordering, proposed to explain the obtained diffraction data. The dependence of the optical properties on these two types of ordering will also be addressed. [1] D. Korotkins, K. F. Ludwig, and T. D. Moustakas, APL 72, (1997).

We have fabricated MOS structures directly on n-GaN surfaces by forming GaNO₃ 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 advantage of photochemically grown oxides is the close proximity of the etching and oxidation within the same procedure (e.g. useful for gate recess technology). On the other hand, the less surface damage is introduced compared to conventional dry etching techniques or sputter deposition methods. The oxides characteristics depend on PEC conditions such as electrolyte composition and applied potential. Further structural analysis of the oxide layers were done using Auger electron spectroscopy, surface profilometry and X-ray diffraction.

Typical 1D -characteristics of the formed MOS structures show a distinct oxide behavior. The negligible reverse currents originate in a strongly depleted region in the underlying GaN. Forward characteristics reveal an insulating behavior of the oxides with resistivities up to 10¹¹ cm⁻¹. Breakdown fields exceeding 0.4 MV/cm. CV-measurements show also good performance within ±4 V at frequencies ranging from 1 kHz to 1 MHz indicating depletion and accumulation behavior for all measured frequencies. The small flatband voltage shift indicates that the CV-curves reveal that only a low density of interface states was introduced by the photoredox growth procedure. Triangular voltage sweeps exhibit small capacitance hysteresis even at elevated temperatures up to 100°C which is due to a small concentration of electron traps within the insulating gallium oxides.

Integration of the oxide formation in a MOSEF device fabrication process is typically hindered by the solubility of the amorphous GaNO₃ layers in acids and bases. We will show how to face this challenge using tungsten as a gate metal. ¹ T. Rötter, D. Misteled et al., Appl. Phys. Lett. 79 (2001), 3925 (2000)

GI11.43 STRUCTURAL ANALYSIS IN REAL SPACE OF Inₐ Gaₜ N SINGLE QUANTUM WELLS BY COAXIAL IMPACT COLLISION ION SCATTERING SPECTROSCOPY: M. Samimi, Dept of E&E Eng., Shizuoka Univ., Hamamatsu, JAPAN; K. Meno, M. Furusawa, M. Yoshimoto, Tokyo Inst of Tech, Yokohama, JAPAN; S. Chidambaram, Inst of Appl Phys, Univ of Tashkent, JAPAN; S. Nakamura, Nichia Chem Industries, Aman, JAPAN.

The intense luminescence from Inₐ Gaₜ N single quantum wells (SQWs) has been considered as the recombination of excitons localized at certain potential minima originating from the compositional variation within the SQWs. Structural analysis of the SQWs has been required both for improving the device performance and understanding the optical properties of Inₐ Gaₜ N alloys. In this contribution, the structures of Inₐ Gaₜ N single quantum wells (SQWs) for are analyzed by COAXIAL IMPACT COLLISION ion scattering spectroscopy (CAICISS). The device-quality Inₐ Gaₜ N SQWs (0.8% to 0.2% c) with 3µm thickness were deposited on 3 µm-thick GaN buffer layers grown by metal-organic chemical vapor deposition (MOCVD). In this process, the He ion beam accelerated at 3keV was used in CAICISS system. After the time-of-flight measurement was made at the normal incidence, the variation of In concentration and Ga signal intensity was observed, changing the glancing and azimuth angle of the He ion beam. An azimuth angular dependence of both In and Ga signals exhibited three-fold symmetry due to wurtzite structure. The alloyed In GaN film (0.8% c) is of high quality, and the film incorporated into Inₐ Gaₜ 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 high In mole fraction. This enhanced disordering of lower In fraction detected by CAICISS is consistent not only with the intense luminescence from Inₐ Gaₜ N SQWs [1], but also with localization in the hole wave function resulting in larger band-gap bowing parameter [9].


GI11.44 IMPROVEMENT OF CRYSTALLOGRAPHIC QUALITY OF GaN LAYERS THROUGH REMOVAL OF SiO₂ MASK DURING LATERNAL EPITAXIAL OVERGROWTH: Min-Hoong Kim, Yong-Ho Choi, Jong-Hyeong Yi, Min Young, Chu-Kyo Kim, Jin Seon and Shi-Jeon Leem, OET Team, Advanced Materials Labs., 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 LEDs and low leakage current FETs. However, crystallographic tilting and high defective region in coincidence In the LEO GaN layers were observed. These defective regions were affected by lateral growth rate and mask materials. 2µm-thick seed GaN layers were grown by MOCVD on sapphire substrates. SiO₂ films were deposited by PECVD on MOCVD GaN layers and 9µm-wide stripes with periodicity of 12µm were patterned along <1 1 1 0> direction. The lateral overgrowth of GaN was carried out by LEO-VCD at various pressures and VCD. The crystallographic tilting of 1/102 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 overgrown GaN and SiO₂ mask. To clarify the effects of SiO₂ mask, it was replaced by wet etching of SiO₂ mask and additional lateral overgrowth was carried out to complete the fabrication of a SiO₂ removed LEO wafer. The crystallographic tilting was not observed in SiO₂-removed LEO samples and the coincidence In the SiO₂-removed LEO samples was sharp and less defects, as observed by CL. We will report the properties of SiO₂-removed LEO GaN layers in detail.


Hydride Vapor Phase Epitaxy (HVPE) in combination with Epitaxial Lateral Overgrowth (LEO) has shown to be very promising to obtain the high quality GaN layers with low dislocation density 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 SiO₂ stripes, aligned along the <1 1 0> and <1 2 1 0> directions of GaN. The cross-section 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 gas as the 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 to propagate in the basal plane. In addition, by changing the direction of the hydrogen flow, the formation of square facets is observed. TEM observations show these bent dislocations and a high density of horizontal defects above the mask. After overgrowth, the surface is flattened in a second growth step under nitrogen. Cross-sectional cathodoluminescence shows basically two regions of luminescence intensity and nature. One showing new backbsp;excitation emission, the other a high intensity blue shifted emission band attributed to e-ha recombinations, indicating a high local free carrier concentration due to intrinsic defects or impurities. These two regions are correlated with different growth facets.


We calculated the LEED parameters and the surface bond 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 (Perdew-Burke-Ernzerhof model) approximation of 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, the factor D(110) = 0.21 Α (LDA) and 0.23 Α (GGA) which can be interpreted as 13.0 degrees(LDA) and 13.0 degrees(GGA); the bond contractions at the
surfaces are 4.1% and 4.3% for the LDA and GGA, respectively. In connection to the band structures, the main differences refer to upward shifts of order of magnitude of the LDA energies as compared to the GGA ones.

**G11.47**

**DILOCATION INDUCED WING ROTATION IN A THICK LEO**


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[210] and 1/3[211] above the edges 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] direction, intersecting sets of 1/3[210] and 1/3[211] type dislocations often combine to form edge dislocations with Burgers vector 1/3[1210]. In addition to the commonly observed ‘wing tilt’ about the LEO stripe axis, (0.5 degrees about [100] in this case), a second rotation of the wings about the [1010] axis was inferred from the Burgers vectors and arrangement of a second set of dislocations that form in the [1100] plane in this thick sample. The rotation of the wings around [1010] has now been measured by focused probe electron diffraction, and the systematic nature of the rotation was confirmed by 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 substrate surface.

**G11.48**

**THE REDUCTION OF DILOCATION DENSITIES IN THE TWO-STEP GROWTH OF GaN BY HVPE, PR, TM, E. Ficke, J. X. Wang, R.H. 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 by HVPE, using the thick GaN film to dereactive the 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 ~10^10 cm^-2. The recent development of a two-step HVPE growth process has revealed a distinctively different behavior, namely that the dislocation density saturates at an order of magnitude or two lower (~10^9 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 500°C and re nucleating on this buffer layer at high temperature. Using x-ray and post growth x-ray and color photoluminescence measurements, we have observed that the dependence of the dislocation density on film thickness. This can be understood by considering previously developed models of threading dislocation density in terms of the formation and subsequent nucleation of mixed type threading dislocations.

**G11.49**

**ORIGINS OF THREADING DILOCATIONS IN GaN EPITAXIAL LAYERS GROWN BY MOVPE, V. Narayanavan, K. Lois, W. Kim, S. Mahajan 1, 2, 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 growth on low temperature GaN nucleation layers grown on c-plane sapphire has been investigated using transmission electron microscopy. 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 12h 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 n type), while pure edge (n type) dislocations are absent. The edge and n type dislocations begin to form at the interior of the island. Contrary to the previous suggestions by researchers, island coalescence may not give rise to pure edge dislocations (n type) as they are absent even after 2 minutes of HT GaN growth. Arguments will be developed to rationalize the above observations.

**G11.50**


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. High mobility in intentionally doped n- or p-type films. Optimized MOVPE growth film has yielded UID-GaN films with resistivity > 10^12 Ω-cm, GaN Si films with mobilities > 300 cm^2/Vs for n = 1x10^16 cm^-3, and GaN with 2DEG mobility of 1500 cm^2/Vs for n = 1x10^14 cm^-3. 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 processes 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 efficiency observed in devices. We observed that the GaN films increase and carbon impurity incorporation decreases with increasing growth temperature, influencing the transport characteristics of the films. Resistivity has been observed to vary from > 10^12 Ω-cm to < 10^10 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**

**MISSING DILOCATION ARRAYS AND FRACTURE IN AlGaN/GaN HETEROSTRUCTURES, D.M. Fullerton, J.A. Flege, S.J. Heane, J.H. Han, and J.J. Figiel, Sandia National Laboratories, Albuquerque, NM.**

Tensile strained AlGaN 2-2/N GaN layers undergo a combined relaxation 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 migration of chemical vapor deposition. The competition between fracture and dislocation introduction appears to be determined initially by limitations on defect nucleation, where surfaces are able to nucleate first at impurities 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. Interacting partials within the heterointerface 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, K. Wang, W.M. Ashmore, M.A. Zikry, R.R. Reeder, Dept. of Materials Science & Engineering, NC State University, Raleigh, NC; 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 relaxation, temperature, and dimensional variations 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 modules empirically estimated for a broad range of temperatures. These are used in conjunction, with specialized finite-element computational techniques, to predict interfacial shear deformations and tensile debonding on physical scales commensurate with thin film layered structures. We are also investigating the synergistic interaction between experimental observations and computational predictions, and material properties can be selected to optimize materials and architectures for layered thin film systems.

**G11.53**

**SURFACE ELEVATION AND STRAIN IN ION IMPLANTED GaN, B. Bokor, S.B. Quddi, S. Schielstein, R.M. Straw, C.A. Carravella, 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 c-in-plane 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 thick oxide and other physical properties. Step height and the implanted and the unimplanted surfaces were made by a KLA
Tenc, PIQ profiler. There is a sharp increase in step height for doses (∼5×1015/cm²) near to the amorphization level. For the same range of doses, the maximum changes in the GaN. Triplet crystals X-ray measurements have been used to obtain the in-plane and out-of-plane 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-plane strain measurement. In addition, the in-plane compression was found insufficient to account for the out-of-plane expansion. Transmission electron microscopy studies indicate void formation around the high-energy vacancy loops (HEL). The 20% increase in step height and the onset of etching 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 THERMALLY DISLOCATIONS IN GaN EPILAYERS BY DIGITAL PROCESSING OF HRTEM. S. Kree, P. Stroeven, V. Potin and G. Noutz, ESCTM-CHISMAT UMBR 65088 CRISTEM. Caen, FRANCE.

The mosaic structure of GaN epitaxial layer (1000) on a 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 core. The measurement performed for individual sub-grains shows quasi continuous misorientation changing across the grain and as large as 4 degrees for 30 nm size grain where measured. The influence of strain field generated by individual dislocations on the sub-grain disorientations map is analyzed by using the map of local rotation of the crystal lattice. Analysis of strain tensor maps shows that for dislocation distances larger than 10 nm the interaction between dislocations is weak. Strong modification of strain field of individual dislocations is observed when the distance is lower than 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 dislocation types of type 1/2 of Burgers vectors of type 1/2 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, J. Kim, S.J. Rhee, J.L. Strange, E.K. Suh, 1, Jeffrey O. White, 1, H.J. Lee, 1, 2, Frederick Seitz Materials Research Lab. University of Illinois, Urbana, IL, 2Semiconductor 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 gives longer lifetime in the brighter area than 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. Korotov and B.W. Wessels, Materials Research Center and Department of MSE, 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 (SPC) 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 × 10¹⁶ to 8 × 10¹⁵ cm⁻³, in contrast with the 1.0 eV level concentration 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

We have measured high resolution [3.3 mm] thermal conductivity k at temperatures before and after plasma induced effects on n-GaN/sapphire (0001) samples fabricated by hydride vapor phase epitaxy (HVPE) using a ThermoMicroscope's scanning thermal microscope (SThM). The simple thicknesses were in the 45-50 nanometer range and the carrier concentrations were 8×10¹⁰ cm⁻³. The thermal conductivity before treatment was found to be in the 1.7k/1.75 W/cmK 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/cmK) compared to the non-treated case. k had dropped to ~0.3 W/cmK 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 work was supported by Office of Naval Research contract Number 1/00014-99-C-0603 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 FI-9528-85-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 SULFIDE. Jennifer A. Himes, James R. Willis, and Daniel A. Golin. Ohio Univ, Dept of Chemical Engineering and Condensed Matter and Surface Science Program, Athens, OH.

The large piezoelectric constants of GaS suggest possible application of GaS-based materials to piezoelectric sensors, among other areas. In this work, films of gallium sulfide approximately 0.75 micron thick and grown by MOCDV were subject to an externally-imposed radial strain condition. Deposition was performed on 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 microscopic head (Mitsuto) mounted to an Ionic Systems Basic Strain gauge (model 30265). Stress levels were calculated based on the magnitude of the imposed deflection, measured from the microscope display, and the piezoelectric response at any particular dot with respect to the center dot was measured by measuring the voltage change using a digital multimeter (Keithley 175). The multimeter head impinged on the center dot and served as the 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 × 10⁻⁵ C/Nm. A discussion of these results will be presented and comparisons made with literature values. The authors gratefully acknowledge partial support under ONR-DURIP N00014-96-1-0782, and J. Himes and J. Willis acknowledge partial support under AFOSR N00014-97-0130.

G11.59
TEM ANALYSIS OF THREADING DISLOCATIONS IN ELO-GaN GROWN WITH CONTROLLED FACE PLATES. Noriyuki Kawanoo, Kyushu Univ, KASTEC, Kagusa, JAPAN. Kazuo Horiuchi, Kawanoo, Kyushu Univ, Dept. of Adv Sci for Electronic & Mater, Kagusa, JAPAN. Hideto Miyake, Kawasaki, Hiramatsu, Mie Univ, Dept of Electronic 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 faceted surfaces of epitaxial (ELO) GaN grown at low growth temperatures with the reactor pressure P₀. Behaviors of
thrending 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 of a [TiN] striped n-SiO$_2$ mask fabricated on MOVPE-GaN/Lt-GaN/sapphire [001]). Two types of GaN films were made in a two-step sequence of switching $T_D$ and $P_L$. They then had a two-layer structure: the lower layer was grown with vertical planes (2T1f) or sloping ones (2T2). The upper layer of both type specimens grew laterally to have a [001]) flat plane. In the former specimen with vertical planes, trending dislocations penetrate straight forwardly to the outer layer of the film. In the latter specimen with sloping facets, on the other hand, trending dislocations turn to the horizontal direction in the lower layer and gather up toward the center of the mask-terrace. These results demonstrate that the morphology of trending dislocations can be controlled by choosing the growth conditions of $T_D$ and $P_L$, and GaN films of an extra-low dislocation-density can be obtained. The behavior of trending 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 WELLS BY USING In$_3$ AS ANTI-SURFACANT. S.J. Chun$^1$, M. Hao$^2$, P. Li$^3$, J. Zhang$^4$, W. Wang$^1$, W. Liu$^1$

$^1$Institute of Materials Research and Engineering, Singapore, SINGAPORE, $^2$Center for Optoelectronics, Dept. of Electrical Engineering, National University of Singapore, SINGAPORE.

The In$_3$, Ga$_{1-x}$N$_x$,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 other to the InGa$_{1-x}$N$_x$N QWs formed by a spinodal decomposition, Stranski-Krastanow (SK) growth mode, or using Si as an anti-surfactant. We report triggering or enhancing the formation of In-rich quantum dots in MOVPE grown InGaN/GaN single quantum well (SQW) by using In$_3$ as an anti-surfactant. Two groups of In$_{0.9}$Ga$_{0.1}$N$_{0.05}$Ga$_{0.95}$N SQWs were grown by MOVPE (Emcore D125) on (001) sapphire substrates. MOVPE was conducted using TMGa, TMIn and NH$_3$ as precursors. For the first group, a 2µm thick undoped bulk GaN was first grown on the 250µ 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 700°C for the deposition of a low temperature GaN barrier and InGaN well layer. After growth of the SQW, a high temperature GaN$_{0.25}$N$_{0.75}$ growth was performed. 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 were 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 480nm for the first and second group of SQWs. The full width at half maximum (FWHM) 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 In$_3$/GaN, In$_3$ acts as an anti-surfactant and lateral segregation of precursors. Besides, In$_3$ also acts as a nucleation centres for the QDs. However, the PL is very sensitive to the TMIn flow rate and too. Large flow rate may result in In$_3$ droplets rather than In$_3$ QDs. SFM shows that the morphology of SQWs is good without any inverted hexagonal pits (HHPs). TEM is being done to investigate the structure of QDs.

SESSION G12: LIGHT EMITTERS AND STRAIN CONTROL

Chair: J. F. Schetzina and Michael A. Kneisel
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 Grondjeau, Benjamin Dribendo, Jean Mesfis, CRHEA-CNRS, Vauconzon, 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 heterostructures are related to the band structure, polarization field and localization effects. Taking advantage of these peculiarities, GaN/AlN QDs emitting light from blue to orange at 300 K can be easily fabricated 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 30% of conduction band localization density. Dislocations in GaN/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 1.65 µm can be observed in single crystal. Carrier localization in GaN QWs is further evidenced by especially designed samples and its origin will be discussed. Finally, this effect is used to realize a single InGaN/GaN QW emitting white light.

9:00 AM G12.2

INTEGRATION OF In$_{0.9}$Ga$_{0.1}$N LASER DIODES WITH III-NITRIDE SUBSTRATE OF LATERAL EMISSIVE STRUCTURE. W. Wang, M. Kneisl, P. Mei, D.W. Tseh, T. Schmidt, M. Tegel, and N.M. Johnson, Xerox Palo Alto Research Center, Electronic Materials Laboratory, Palo Alto, CA.

The combination of its high-temperature stability, similar crystal quality with the III-nitride, and its relatively low cost has made GaN the substrate of choice in development of III-nitride-based blue laser diodes (LDs). The high thermal resistance of the GaN substrate and the relatively high current densities combine to degrade the device performance and lifetimes due in part to 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 infeasible 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 GaN to another host substrate.

As a demonstration of this methodology, prefabricated In$_{0.9}$Ga$_{0.1}$N-based multiple quantum well (MQW) LDs on GaN substrates were successfully transferred from GaN to a GaN-on-sapphire substrates. The separation of the LDs from the GaN substrate was accomplished by using a laser lift-off (LLO) process 1 in which a single XeCl excimer laser pulse was directed through the transparent substrate. Heating the structure above the melting point of GaN ($T_{mel}=330°C$) after laser processing completed the separation and transfer process. Characterization of the In$_{0.9}$Ga$_{0.1}$N LDs before and after the substrate removal revealed no measurable degradation in device performance. The threshold current, under pulsed operation, 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-aligned LD using the Cu as a back contact. Electrical measurements from such a vertically-connected LD showed enhanced L-V characteristics. Additional results from In$_{0.9}$Ga$_{0.1}$N-based LDs fabricated with an epitaxial-liner overgrowth technique will also be discussed. The transfer of the In$_{0.9}$Ga$_{0.1}$N MQW LDs from substrate onto Cu substrates demonstrate the efficacy of the LLO process to integrate these LDs onto virtually any substrate material.

9:15 AM G12.3

UV EMMITTER BASED ON HIGH-EFFICIENCY GaN/Al$_{0.9}$Ga$_{0.1}$N MULTI-QUANTUM WELLS. Motoki Iwano, Ryu Nakamura, Shinji Terao, Tatsubu Uki, Dept. of E&E Eng., Meijo Univ., Nagoya, Japan; Satoshi Kamioka, High Tech Research Ctr., Nagoya Univ., Nagoya, Japan; Hiroshi Am Furyo, Isamu Akasawa, Dept. of E&E Eng., Dept. of MS&E and High Tech Research Center, Meijo Univ., Nagoya, JAPAN.

Solid state UV light will surely give a big impact on the optoelectronics 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-radioactive component with increase of the AIN mole fraction in AlGaN as well as the difficulty in achieving highly conductive p-type AlGaN had obstructed the realization of UV light source based on nitrides. Recently, we succeeded in growing highly-crack-free and high-crystalline quality Al$_{0.95}$Ga$_{0.05}$N by using a low-temperature (LT) AlN interlayer, which was deposited on GaN/Lt/buffer/sapphire. High-sensitivity frame sensor was demonstrated using this technique. However, the emission efficiency of Al$_{0.95}$Ga$_{0.05}$N thus grown was still limited by the non-radioactive components. Here we proposed a new growth process of high-harmonics and highly efficient UV emitter based on Al$_{0.95}$Ga$_{0.05}$N. Ga$_{0.6}$Al$_{0.4}$N or Ga$_{0.8}$N$_{0.2}$N MQWs grown by this new technique contains threading dislocations as low as 5x10$^5$ 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 30 K, the PL efficiency is completely different each other. Si doping was found to improve the PL efficiency at RT. Some order of magnitude. In addition, reduction of threading dislocation density improves the PL efficiency by a factor of 10.
intensity of low-darkness-density Si-doped MQW is almost the same as that of GaAs and AlGaAs/GaAs MQWs for LEDs. Control of conductivity, however, was clearly resolved by the detection layer. This work was supported in part by the Japan Society for the Promotion of Science and the Ministry of Education, Science, and Culture of Japan, (contract number 11450131, 12450117 and 12850506).

9:30 AM *G12.4
GROWTH AND CHARACTERIZATION OF AlGaN/GaN DBR
MICROWAVE FET (MIFET) DEVICES

Vertical-electricity surfaces-emitting devices are expected to improve emission directivity 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. 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 interval strain from tension to compression, as verified by an in-situ stress meter. The modulation and evolution of stress during the alternating growth of AlGaN and GaN in a DBR structure was observed by the stress monitor. Nomarski microscopy from a 6 × 6, 100 nm thick, indicated smooth surface with cracks separated by at least 200 to 300 nm; some images were completely crack-free. X-ray diffraction showed satellite peaks to the fifth order. Reflectivities up to and beyond 95% have been measured in GaN/AlGaN multilayer DBR stacks in the wavelength range of 376-380 nm. The in situ DBR mirrors have been incorporated into vertical cavity structures which include GaN in active QW light-emitting region and high reflectivity SiO$_2$/SiO$_2$ dielectric DBRs. We have studied the performance of these microcavities by photoluminescence and electroluminescence measurements, 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

The luminescent 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 MOVCD epitaxy, device design, and manufacturing. The primary advantages of LEDs over conventional lighting technologies are reliability, energy efficiency and the power spectrum. The luminescent efficiency and high cost of LEDs-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 in power levels above 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 manufacturing of InGaN LEDs, and we will present a preview of these future challenges.

10:45 AM *G12.6
CURRENT INJECTION UV-EMISSION FROM InAlGaN MULTIQUANTUM-WELL LIGHT-EMITTING DIODES

Current injection ultraviolet (UV) emission from InAlGaN multi-quantum-well (MQW) light-emitting diodes (LEDs) have been demonstrated. III-nitrides are currently of great interest for application to UV lasers and LEDs. We have already reported that InGaN/AlGaN alloy shows high photoluminescence intensity at room temperature [1]. In this report, we demonstrate UV electroluminescence (EL) from InAlGaN MQW LEDs. The Al content of the MQW LEDs was increased from 10% to 30%. The Al content of the MQW LEDs was increased from 10% to 30%. The EL intensity of the MQW LEDs was increased from 10% to 30%. The EL intensity of the MQW LEDs was increased from 10% to 30%. The EL intensity of the MQW LEDs was increased from 10% to 30%.

11:00 AM *G12.7
CONTROL OF STRAIN AND DEFECTS IN NITRIDE MOVPE
Hiroshi Amano, Motoki Iwasa, Shogo Naka, Shintaro Terao, Ryo Nakamura, Satoshi Kaminuma, Christian Wettel, 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 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-crystalline laser beam in a vertical direction. The problem of strain and defects would be serious if we move on to much shorter wavelength region. AlN containing alloys are much more sensitive to the non-radiative center than InN containing alloys. Increase of both strain and non-radiative centers during the growth can become a serious problem. Understanding the physical properties of nitrides at growth temperature gives a guideline to realize high-quality and crack-free AlGaN alloys and their heterostructures. We achieved low dislocation density thick Al$_x$Ga$_{1-x}$N with x up to at least 0.45. PI 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. Tsuda, Y. Korotev, S. Watanabe and N. Yamada, AIGL Technologies for help with the experiments. This work was partly supported by JSPS (539050294) and MEXT (11450131, 12450117 and 12850506).

11:30 AM *G12.8
CONTROL AND ELIMINATION OF CRACKING OF AlGaN THIN FILMS USING LOW TEMPERATURE ALGaN INTERLAYERS

The ability to produce short wavelength optoelectronic devices based on AlGaN has been severely hindered by cracking of the AlGaN layers due to the large lattice mismatch. We have demonstrated that the use of low-temperature AlGaN interlayers is effective in reducing the coherency stress when AlGaN grown at high temperature on GaN pseudosubstrates. The stress evolution during growth was monitored using in situ wafer curvature-based stress sensor and was correlated to exc 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% Al-containing AlGaN layers, we found that the initial growth stress changed from tensile as the aluminum concentration in the AlGaN interlayer was increased. Furthermore, the crack density in the 20% AlGaN films decreased from very dense to cracking of the AlGaN layers. 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 control 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 GI1.2
IMPROVED OPTICAL QUALITY OF GaInN QW STRUCTURES GROWN ON Si-SUBSTRATE BY CONTROLLING RESIDUAL STRAIN USING MULTI-BUFFER LAYER.
Hideo Kawasaki, Tokyochi Takano, Makoto Kurimoto, Yoshikazu Shibata, Manabu Horie and Junichi Yamamoto, Yokohama University, Dept of Electronic Engineering, Tokyo, JAPAN.

BAiGaN quantum system grown on Si substrate or AlN is one of a lattice matching nitride system with high potential use to light emitting devices (350nm to 380 nm wavelength range). However, it was complex to grow the BGN, BAiS and BAiGaN, which include Boron in the nitride system, optionally on the substrates by Metal-Organic Vapor Phase Epitaxy. Optical properties of the epilayer of the BGN and BAiGaN grown directly on the Si-substrate has been improved for device applications. For this purposes, BAiGaN (AIn) MQW structure was grown on residual strain controlled thin AlN layer using (GaN/AiN) Multi-Buffer layer. Crystal quality and surface flatness of the [BAiGaN/AIn] MQW structure was drastically improved by introducing the strain in thin AlN layer with (GaIn/AIn) Multi-Buffer layer, and shortest PL wavelength obtained from the [BAiGaN/AIn] MQW was as short as 245nm at room temperature. On the other hand, maximum Boron composition included in BGN was 7%, from which room temperature PL spectral was obtained, in this time. But, the shortest PL wavelength of the BAiGaN quantum well was not strongly depend on the Boron content, but also Al composition. However, optical characteristics of the PL spectra from the BAiGaN MQW depend on the residual strain included in the epitaxial layer.

SESSION GI3. LIGHT EMITTERS AND ELECTRONIC DEVICES.
Chair: Seve A. Stokker and Jun Hong
Friday Afternoon, December 1, 2000
Room 216 (Hynes)

1:30 P.M. GI3.1
EUROPEAN ACTIVITIES ON GaN LEDS AND BLUE LASERS.
Volker Hille, Georg Brüderl, Johannes Baer, Dominik Einert, Stefan Bäder, Bernd Hof, Hans-Jürgen Lugner, Andreas Weimar, Alfred Leit, OSIAM 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, laser projector 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 diode with low threshold currents, lifetimes in the order of 10,000 hours etc. Some main European activities are focused on a cooperation of OSIAM Opto Semiconductors, the universities of Stuttgart, Braunschweig and Ulm, as well as the Fraunhofer Institute in Freiburg, resulting in first pulsed laser operation in July 1999. The work was carried out on SiC wafers using LT-MOPVE. The growth on SiC allows fast and easy processing due to the possibility of a single 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 obtained. 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 10nm. 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/cm². Lowest threshold current densities of 330µA were reached at 410nm emission wavelength for 4µm wide and 450µm long stripe mirrors with mirror coatings of 98% and 70% reflectivity. Characteristics temperatures up to 280K indicate the good electrical confinement of our epi structure. On the top of the laser results OSIAM Opto Semiconductors have demonstrated high brightness LEDs with more than 7mW at 465nm emission wavelength which is to our knowledge record for SiC based devices. These technological improvements indicate the competition in the future. Part of this work was supported by the German Government [1]. D.A. Stokker et al. Appl. Phys. Lett. 73 (1998) 1955.

2:00 P.M. GI3.2
IMPROVED OUTCOUPLING EFFICIENCY OF GaN BASED UV-LEDs.
V. Schwegler, S. Schad, M. Seyboth, M. Scherer, C. Kirchner, M. Kump, Dept. of Optoelectronics, University of Ulm, Ulm, GERMANY.

Currently there is a strong research interest on GaN-based light emitting diodes (LEDs) including integrated optical waveguides and for UV-LEDs in combination with luminescence converters are possible for fundamental elements for production of white LEDs, which could replace common lighting components like incandescent lamps in the future. Although GaN [GaN/AIn] has a smaller refractive index as most other III-V-semiconductors (e.g. InGaAs, InGaP) 3.4) 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 the maximum efficiency can also be decreased. 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 pyramids) are still to be evaluated and translated into a functional efficiency. We estimate the influence of various contact facets on the IV- and optical characteristics of UV-emitting LEDs. This includes the particular transmission measurements in dependence of metallization scheme [Ni/Au, Pt], metal thickness (5-15 mm, Ni/Au [4/46 mm]: 19/45 transmission at 400 nm without annealing), and thermal treatment (N2 vs. O2 atmosphere). It is shown that external quantum efficiency is strongly depending on chip size and mesa geometry. A multi-emitter structure is presented which allows improved outcoupling efficiency by 26-29% in comparison to standard design. The output characteristics of the examined devices were conformed 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 P.M. GI3.3
DEMONSTRATION OF ELECTROABSORPTION EFFECT IN InGaN/GaN MQW LAYERS USING AN INTEGRATED LED/MODULATOR/DETECTOR DEVICE STRUCTURE.

Being non-centrosymmetric, 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 (QCE) 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 InGaN and GaN barrier layers. The strong piezoelectric effect and QCE in the InGaN QW structures allow one to manipulate the free carrier absorption by the extrinsic electric field. However, most of previous studies are conducted at the material level based on optical measurements such as photoluminescence, photoconductive and electroabsorption[3], rather than on fabricated devices. In the present work, we fabricated a planar integrated three-section LED/electroabsorption modulator/detector structure on a In0.6aGa0.4aN/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 structures were used to reduce diffusion length. From the end results, the experimental results showed that the detector signal (200mV) was due to the light emission from the LED section decreases monotonically with increasingly 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 w.r.t. QCE when a reverse bias was applied to the modulator. The maximum quasi-modulation efficiency of between the detector and the modulator is found to be 22% at 100kHz on the condition of In0.6aGa0.4aN/GaN MQW structure. Work is currently underway to characterize In0.6aGa0.4aN/GaN MQW structure with varying In composition and hence the piezoelectric field at x = 0.1 and 0.27 respectively. 1) T. Tsuchida, S. Sota, M. Katsuragawa, M. Komori, H. Tsuchiya, 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. Chiba, T. Arimura, T. Sota, and S. Stokker, Appl. Phys. Lett. 69, 4188 (1996)

2:30 P.M. GI3.4
MODIFICATION OF A HIGH POWER GaN METAL SEMICONDUCTOR FIELD-EFFECT TRANSISTOR.
Seikoh Yoshida and Hirotsugu Ishii, Yokoohama R&D Laboratories, The Hitachi Electric Co., Ltd, Yokoohama, JAPAN.

GaN and related materials are very suitable for the electronic devices which can be used under high-temperature, high-frequency and high-power conditions. The physical properties of GaN are strongly dependent on the density of defects. Therefore, it is necessary to improve the device property. The modification of the Mn-related defects has recently been studied. In this talk, the results of the Mn-related defect modification of high power GaN-Metal semiconductor field-effect transistor will be reported. The efficiency of the Mn-related defects modification has been proved by the growth of GaN:Mn. By the Mn-related defects modification, the channel length dependence of the drain-source current in a GaN-Metal semiconductor field-effect transistor has been improved.
high-power conditions. GaN devices have large figure of merits for these purposes, since the GaN has a wide bandgap, a high breakdown field, and high mobility. In this paper we report on the semiconductor field effect transistor (MESFET) for operating at a very high 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, 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 fingers gates were used for the measurement. The maximum current density and the gate length was 2 μm. The source and drain also had a multi-finger structure. The electrode materials of the source and the drain were Al/Al and the Schottky electrodes were Pt/Al. The mobility of the gate source, source, and drain were isolated using SiO2. The distance between the source and drain was 30 μm. The FET structure was fabricated using a dry etching technique. Multi-electrode structures were also fabricated using SiO2 for isolating the source, drain, and gate electrodes respectively. The MESFET was operated at a current of over 10 A. The breakdown voltage was about 400 V. The transconductance $g_{m}$ was about 10 mS/mm. The pinch off voltage was about -10 V. We confirmed that this GaN MESFET can also be operated as a current of over 10 A. Therefore, a high-power GaN MESFET was thus demonstrated.

2:05 PM G13.3
LOW FREQUENCY NOISE IN GaN FIELD EFFECT TRANSISTORS. Sergei L. Rumyantsev, Neelam Pal, Michael S. Shur, Rensselaer Polytechnic Inst., Dept. of Electrical, Computer, and Systems Engineering, Troy, NY; Remin Gaskin, Xuhong Hu, Sensor Electronics Technology, Inc., Latham, NY; Asif M. Khan, Gregory S. Shriver, Jimmy Lin, Univ. of South Carolina, Dept. of Electrical and Computer Engineering, Columbia, SC; Michael G. Levinstein, Ioffe Institute, 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 (MOSTFETs). The structures were grown by low pressure MOCVD on sapphire substrates. A 1.5 μm undoped GaN layer was followed by the deposition of 60 nm GaN with doping level of 10^{18} cm^{-3}. The transistors had source-drain spacing of 4 μm and a gate length of 1.5 μm. In order to fabricate MOSTFETs 10 nm thick SiO2 layer was deposited on one part of the wafer prior to gate metallization. The other part of the wafer was used for the MESFET fabrication. At 300K, the spectral density of drain current fluctuations $S_I$ had the form of 1/f noise both in MESFETs and MOSTFETs. 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 $Hoege$ parameter $α = 10^{-2}$, this is one order of magnitude lower than it was reported for GaN layers and comparable to that in typical GaN based heterojunction field effect transistors. Measurements using transmission line model (TLM) structures showed that the contacts did not contribute much to the noise. The analysis of the spectrum noise 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

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 changes in the low field mobility than to changes in the series resistance, especially for power microwave devices 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 cm²/Vs and the gate length of 2 μm, these devices demonstrate the measured output power of approximately 3.4 W/mm at 2 GHz. Further improvements can be achieved by scaling down the gate length and the source-drain separation. We conclude that GaN-based MESFETs outperform GaAs-based MESFETs. Our calculations predict that short-channel [0.1 μm] GaN MESFETs might compete with GaN-based High Electron Mobility Transistors.

3:45 PM G13.7

We report on large periphery pseudomorphic AlGaN/InGaN and AlGaN/GaN/HEMTs and MOSTFETs fabricated on sapphire and SiC substrates. Our results show that HEMT and MOSTFET performance is very close, with similar maximum drain currents on the order of 0.6 to 0.8 A/mm, and maximum frequencies of oscillations (with 1-f product) on the order of 12 to 16 GHz microsec, etc. However, the MOSTFETs have several orders of magnitude smaller gate leakage current and a lower 1/f noise. These 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 explained a double channel design for minimizing the source series resistance and the microwave noise. CW and pulse microwave power data will be presented. We conclude that pseudomorphic AlGaN/InGaN and AlGaN/GaN/MOSTFETs might have an advantage for applications requiring low 1/f noise and, as a consequence, a low noise phase.

4:00 PM G13.8
Ta BASED OHMIC CONTACT ON AlGaN/GaN HETJET STRUCTURES. D. Qin, L. Jin 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 metalization is commonly used for aluminum contacts to n-GaN and related compounds. We have previously reported the development of an ohmic contact 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 layer in the HFET structure. These reactions consume part of the barrier, 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 less on AlGaN/GaN (300K) or AlGaN HFETs. There are two drawbacks of this the Al/Ti based advancing interface scheme, (i) it requires a copper 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 schematic lithographic alignments. For these reasons, we developed a Ta based "advancing" contact scheme for HFET structures. The presence of Ta in this scheme lead to efficient electron emission without requiring cop layers for the ohmic annealing. In this demonstration, electrical and structural results will be discussed.

4:15 PM G13.9

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/TiN/Au) and Schottky contacts (Pt and Ni) were implemented 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 gate layer structure (sheet resistance of 500 ohm/square, 20% Al). For the ohmic contacts, we has found 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 a function of different pre-metalization HEL 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. In this part of the work we also compared 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-CMOS modes, finite substrate thickness is discussed. The consequences for the matching network of a typical HEL will be presented.

4:30 PM G13.10
P-GaAs/GaN HETEROJUNCTION DIODES AND THEIR APPLICATION TO HETEROJUNCTION BIPOLAR TRANSISTORS. Toshiki Mikimoto, Kazuhide Kunikura, Nozomi 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^{18} 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 8.0 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.