Electronic Materials and Processing Division
Room 608 - Session EM-MoM

Nitride Epitaxy

Moderator: M.R. Melloch, Purdue University

8:20am **EM-MoM1 GaN Growth Chemistry, System Design and Materials Properties**, ***T.F. Kuech***, *J. Sun, L. Zhang,* University of Wisconsin, Madison; *J.M. Redwing,* Epitronics **INVITED**

The growth of device-quality GaN by metal-organic vapor phase epitaxy (MOVPE) is often difficult to achieve. The MOVPE growth of GaN is complicated by the extensive and pervasive complex gas phase chemistry within the growth system. This gas phase chemistry leads to the high sensitivity of the materials properties on the detailed fluid dynamics within the system. Through the combination of reactor modeling and gas phase kinetic studies, we have identified a stratified gas phase chemical structure within the reactor that leads to such process complexities. The high gas phase flow rates employed in GaN MOVPE results in a very thin high-temperature gas flow region above the growth front that leads to extremely high thermal gradients. Inside this thin high-temperature flow region, dominant chemical species above the growth surface changes in the gas phase above the growth front as a result of the high thermal gradient present and the high molecular weight species resulting from the oligimerization of the adduct. This chemically stratified region is closely related to the transport and reaction behavior present in GaN MOVPE processes and the modeling of this near-growth-front region serves as an engineering guideline for GaN MOVPE reactor design. We have combined these numerical results with detailed experimental measurements within the modeled system. The implications of these findings for the design of GaN systems and materials performance will be discussed. The extension of these models to the case of selective are growth of GaN will be discussed in terms of the local gas phase activities of the reactants and their influence on the facet formation.

9:00am **EM-MoM3 Mechanisms for Lateral Growth and Coalescence in GaN CVD**, ***M.E. Bartram***, *M.E. Coltrin, J. Han, C.C. Willan,* Sandia National Laboratories

Recent observations of rapid coalescence occurring upon convergence of lateral growth fronts suggest new strategies for GaN selective area growth (SAG) techniques. A mask with systematically spaced nucleation zones was used to provide a pseudo time-base for observing lateral growth transitions within a single GaN deposition. Scanning electron microscopy (SEM) revealed that the joining of adjacent features initiated a secondary lateral growth mechanism. The profile of the coalescence region suggests this rapid mode of deposition was controlled by layer-by-layer growth in which each new growth surface defined a reactive step against the initial growth front for nucleation of the next layer. This buildup thus driven by the lateral rate, resulted in the vertical growth front in the coalescence region meeting the upper most surface of the initial growth features. The layer-by-layer coalescence mechanism was quite independent of the slower progress of the original growth fronts when the V/III ratio was sufficiently high. However, it was non-existent under low V/III conditions. Correlations with materials quality will be made using TEM and CL measurements.

9:20am **EM-MoM4 Selective Area Growth of GaN on Si by Chemical Beam Epitaxy**, *E. Kim,* ***A. Tempez***, *N. Medelci, I.E. Berishev, A. Bensaoula,* University of Houston

One possible advantage of high vacuum deposition techniques over MOCVD is the realization of GaN device structures on Si wafers. In the case of MOCVD and sapphire substrates, selective GaN lateral regrowth over SiO@sub 2@ masks has been shown to reduce considerably the defect density in the epilayers. Thus far, very little data is available for regrowth using MBE techniques. In our previous studies of GaN deposition by chemical beam epitaxy (CBE) with TEGa and ammonia precursors, we have shown that no nucleation occurs on a sapphire surface. Using the same CBE precursors, we investigate here the selective nucleation process on Si wafers patterned with various oxide and nitride masks. The selectivity of the nucleation process was monitored in real time using time of flight ion scattering and recoil spectroscopy and RHEED. Two direct recoil spectroscopy (DRS) detectors mounted at 40 and 70° recoil angles are associated with MSRI (mass spectroscopy of recoiled ions) analyzers (sector and reflectron, respectively). These time refocusing analyzers allow for higher resolution and sensitivity than DRS. Our results show that the MSRI Si to O peak intensity ratio during GaN regrowth of SiO@sub 2@ patterned GaN is constant within the condition range we explored. This shows a 100% selective overgrowth process and is confirmed by SEM analysis. Following these experiments, we then implemented various regrowth schemes such as the use of a thin AlN single crystal layer on Si by a reactive MBE method followed by patterning and etching in an Ar-Cl@sub 2@-BCl@sub 3@ RF plasma. In this presentation, we will summarize our observations on the effect of the growth conditions (growth temperature and Ga/N flux ratio) on the selectivity of the nucleation process and will show our most recent data on the optimized regrown GaN layers- including their optical, electrical and field emission properties.

9:40am **EM-MoM5 The Role of Extended Defects in the Physical Properties of GaN and its Alloys**, ***J.S. Speck***, University of California, Santa Barbara **INVITED**

GaN and its alloys have emerged as the leading wide bandgap materials system for electronics and optoelectronics applications despite the high extended defect densities encountered in state-of-the-art device material. Pure edge character ('a' Burgers vector) or mixed character ('a+c' Burgers vector) threading dislocations with densities in the mid-108 to 1010 level are the predominant extended defects in high quality MOCVD-grown GaN on sapphire or silicon carbide substrates. We review the origin of these along with other extended defects (e.g., stacking disorder and inversion domains) and relate the growth to basic capillary-governed growth phenomena. Recently, a new technique, lateral epitaxial overgrowth (LEO), has emerged as a technique to reduce the density of extended defects by 3 - 4 orders of magnitude. The basic growth processes and extended defect evolution in LEO growth will be presented LEO GaN can also be used to directly compare the physical properties of dislocation-free and dislocated GaN. We show in experiments on LEO and 'normal' (bulk) GaN that threading dislocations behave as charged scattering centers, non-radiative recombination centers, and current leakage paths. Additionally, threading dislocations are the most common origin of deviations from planar growth and lead to a variety of kinetically-limited growth morphologies. Finally, highlights of some of our recent work on MBE growth of GaN will be presented, including record mobilities for 2-dimensional electron gas in AlGaN/GaN heterostructures.

10:20am **EM-MoM7 Growth Kinetics of GaN(0001) as Grown by MBE@footnote1@**, ***A. Parkhomovsky***, *S.M. Seutter, B.E. Ishaug, A.M. Dabiran, P.I. Cohen,* University of Minnesota; *S. Keller, S.P. DenBaars,* University of California, Santa Barbara

The kinetics of growth of GaN films using molecular beam epitaxy with a Ga K-cell and an NH@sub 3@ leak was studied. GaN(0001) layers grown by metalorganic chemical vapor deposition on c-plane sapphire were used as substrates. In situ growth monitoring was conducted using reflection high energy electron diffraction (RHEED) and desorption mass spectroscopy (DMS). The films were characterized in situ by UHV scanning tunneling microscopy (STM) and ex situ by atomic force microscopy. Prior to the growth the substrates exhibited a 2D RHEED pattern characteristic of a smooth surface with atomic steps. Initial growth of GaN under Ga rich conditions on this surface at 760°C produced a rough surface as indicated by a 3D RHEED pattern. We suggest that the roughening is due to a surface contamination that changes the growth kinetics, causing faceting of the surface. The surface was then gradually smoothened by growing under the same excess Ga conditions. On a smooth surface, RHEED intensity oscillations were observed for both the excess Ga and excess NH@sub 3@ growth regimes. This is very different from the GaN(000-1). Like the GaN(000-1), the RHEED oscillations were observed in the excess NH@sub 3@ regime at Ga beam equivalent pressures ranging from 3x10@super-7@ to 5x10@super-7@ Torr and an ammonia BEP from 0.5x10@super-4@ Torr to 1.0x10@super-4@ Torr at a substrate temperature of 600°C. Unlike GaN(000-1), the RHEED oscillations were seen in the excess Ga regime at a Ga BEP of 1.4x10@super-6@ Torr, NH@sub 3@ BEP of 1.6x10@super-7@ Torr and at a substrate temperature of 760°C. Upon initiation of the Ga flux, DMS measurements indicated a single step increase in the Ga desorption signal which is different from the two-step increase on the GaN(000-1) associated with a physisorbed state. UHV STM studies were conducted on fully gallided and partially nitrided quenched GaN surfaces. Partial nitridation of GaN(0001) surface in ammonia produced nitrided zones at step edges that are 15-20 nm in size and 2-3 ML deep. The size of the zones is much less than that on the GaN(000-1) surface. @FootnoteText@ @footnote1@ Partially supported by the Office of Naval Reasearch and the National Science Foundation

10:40am **EM-MoM8 Dissociation of Al@sub 2@O@sub 3@(0001) Substrates, and the Roles of Silicon, Oxygen, and Nitrogen Vacancies in n-type GaN Grown by MBE**, ***J.E. Van Nostrand,*** Air Force Research Lab*; J.S. Solomon,* University of Dayton Research Institute*; A. Saxler,* Air Force Research Lab

GaN is a semiconductor material that shows great promise for use in optoelectronic and electronic devices due to its large, direct bandgap. However, in spite of astonishing and rapid developmental successes, many problems remain that hinder further progress. Among them is a lack of understanding of the mechanisms underlying impurity incorporation, the nature of native defects, and the dependence of both of these on the thermodynamics and kinetic limitations of the GaN growth technique employed. One nearly universal aspect of unintentionally doped GaN films grown on sapphire by any technique is an n-type background carrier concentration. This phenomenon has been attributed to impurities such as Si or O, or to native defects such as N vacancies. In this work, we identify and quantify an anomalous relationship between the Si doping concentration and free carrier concentration and mobility using temperature dependent Hall measurements on a series of 2.0 µm thick GaN(0001) films grown on sapphire with various Si doping concentrations. Secondary ion mass spectrometry (SIMS) is used to identify the type of the excess free carriers to be oxygen. Further, the source of the oxygen is positively identified to be dissociation of the sapphire substrate at the sapphire-nitride interface. Finally, SIMS is again utilized to show how Si doping can be utilized to control the diffusion kinetics of the oxygen into the GaN layer from the sapphire substrate.

11:00am **EM-MoM9 Growth of GaN Thin Films and Device Structures on Silicon Wafers by Molecular Beam Epitaxy**, ***I.E. Berishev,*** *D. Starikov, N. Medelci, A. Bensaoula, I. Rusakova, E. Kim,* University of Houston

GaN grown on Si wafers has large perspectives in various device applications due to low cost of the substrate and easy integration with well developed Si circuits. More over, molecular beam epitaxy is advantageous in this respect due to low growth temperature and advanced methods of in situ characterization. We report the growth of GaN - based heterostructures and light emitting devices on Si (111) wafers by molecular beam epitaxy with a RF nitrogen plasma source. We found that the buffer layer between the Si and the GaN epilayer is the most critical factor responsible for the properties of the active device layers. To that end, several buffer layers, including AlN, GaN and Si-@sub x@N@sub y@ were studied in situ by RHEED and time of flight mass spectroscopy of recoiled ions and ex situ by transmission electron microscopy. Inter-diffusion between Si and Al(Ga) was studied by SIMS. We found that diffusion of group III elements into the substrate is much stronger than diffusion of Si into the upper layers. Optimized growth conditions for the buffer layer, the thick GaN layer, and p-type GaN layer allowed for injection light emitters to be fabricated. Ternary alloys, including InGaN quantum well active regions, are currently under development. Our most recent data on X-ray diffraction, photo-luminescence and electro-luminescence of fabricated light emitting diodes on Si (111) wafers will be presented at the conference.

11:20am **EM-MoM10 Photoluminescence and Heteroepitaxy of ZnO on Sapphire Substrate (0001) Grown by RF Magnetron Sputtering**, ***K.K. Kim,*** *S.J. Park,* Kwangju Institute of Science and Technology, Korea*; J.-H. Song,* Korea Institute of Science and Technology, Korea*; H.-J. Jung, W.K. Choi,* Korea Institute of Science and Technology, Seoul

ZnO thin films were epitaxially grown on Al@sub 2@O@sub 3@ (0001) single crystalline substrate by RF magnetron sputtering with the variations of RF power P=60-120 W. Crystalline structure of the ZnO films were analyzed by 4-circle X-ray diffraction, backscattering (BS)/channeling, and transmission electron microscopy. At the substrate temperature 550@super o@C, the ZnO film deposited with power of 80W has narrowest full width half maximum(FWHM) of @theta@-rocking curve, 0.16@super o@, indicating an highly c-axis oriented columnar structure. XRD @theta@-rocking curve FWHM of the ZnO film deposited at 120 W and 600@super o@C was 0.13@super o@ and in-plane of ZnO grown on sapphire(0001) substrate was found to be indicated a 30@super o@ rotation of ZnO unit cell about sapphire(0001) substrate. In BS/channeling study, channeling yield minimum (@chi@ @sub m@) was changed with growing temperature and power, and was only 4-5% for the films deposited at 120 W, 600@super o@C. In PL measurement, only the sharp near band edge (NBE) emission were observed at room temperature for the films deposited at 80-120 W and 550@super o@C and 120 W, 600@super o@C. but deep-level emission were also detected in the films deposited at 60 W, 550@super o@C. The FWHM was decreased from 133 meV to 89 meV as RF power increased from 80 W to 120 W at 550@super o@C, and that of film deposited at 120 W and 600@super o@C showed 76 meV which is lower value than any other ever reported, which were somewhat opposite to that of XRD. From TEM analysis, grain size and defect were found to affect the PL properties. In this study, the PL property of undoped ZnO thin films is discussed in terms of the crystalline structure and the quality of grain.

11:40am **EM-MoM11 Characterization of a Very Thin Film: N2 Plasma Nitridation of GaAs (110)**, ***J.E. Hulse,*** National Research Council of Canada, Canada*; D. Landheer, R. Krishnamurthy, S. Moisa,* National Research Council of Canada

GaAs (110) wafers were prepared by cycles of UV-ozone/HF cleaning and inserted into an Ultra-High Vacuum processing system. Nitridation of the wafers by a remote Electron Cyclotron Resonance (ECR) nitrogen plasma produced a porous GaN film of up to about 3 nm in thickness. In situ analysis by X-ray Photoelectron Spectroscopy (XPS) revealed that the plasma both scoured the GaAs substrate surface of carbon and oxygen and produced a GaN film. Ex situ analysis by Spectroscopic Ellipsometry indicated that the GaN layer was porous. Angle-Dependent XPS demonstrated that the GaN layer contained traces of As predominantly in the outer regions of the film, and that the porous GaN can absorb water on exposure to air. A 5 second exposure of a GaAs (110) wafer to the ECR nitrogen plasma simulates the initial stage of ECR plasma deposition of silicon nitride, which exposes the substrate to a nitrogen plasma at turn-on. Such a short nitridation produced a GaN film that was 1.9 nm thick with traces of arsenic throughout and approximately 50 % voids. Longer exposures to the nitrogen plasma produced films whose thicknesses followed an inverse power law time dependence. The wafers were examined by Atomic Force Microscopy both before and after nitridation. Before plasma nitridation, the cleaned wafers showed clearly identifiable roughness features due to chemical-mechanical polishing. Plasma nitridation left the surface smooth and free of identifiable features less than 10 microns in lateral size.

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