Monday, Morning, May 24, 1999

Session I

Nitrides: Chemistry

8:20 AM

Isolation and Identification of Precursor Reaction Products in GaN and AlGaN CVD: *Michael E. Bartram*[1]; J. Randall Creighton[1]; Christine C. Willan[1]; J. Han[1]; [1]Sandia National Laboratories, Dept. of Chem. Proc. Sci., MS 0601, Albuquerque, NM 87185-0601 USA

Parasitic reactions between precursors often limit the growth conditions in a CVD reactor, restricting strategies to less than ideal for achieving an optimal set of materials properties. Preferably, the chemistry would be altered to remove these complications from the CVD environment. In lieu of this however, the allowable pressures and flow rates for precursors most susceptible to initiating undesirable reactions must be established. In either case, the reaction products must first be isolated and identified. In this work, quadrupole mass spectroscopy (QMS) and infrared spectroscopy (FTIR) were used to identify and study the products resulting from the reactions between GaN and AlGaN precursors. The reaction between trimethylgallium (TMG) and NH3 produced a Lewis acid: base a NH3 which was sufficiently stable to yield a parent peak in the mass spectrum. This first direct identification of the TMG: NH3 adduct with QMS makes it amenable for controlled studies of the decomposition kinetics as they apply in a CVD reactor. In contrast, bis(dicyclopentadienyl) magnesium (MgCp2), proposed previously to react with ammonia, has now been suggested with FTIR studies of immobilized reactants to react instead with water impurities in the ammonia to produce MgO particles. Finally, the observation of solid particles formed when both trimethylaluminum (TMA) and MgCp2 are present in the reactor inlet is the result of a well known reaction yielding alkyl alumino-magnesium compounds. Pressure and flow rate dependencies necessary for precursor reactions to occur will be reported.

8:40 AM

Alternative Dopant Sources for GaN:Mg: *William S. Rees*[1]; Oliver Just[2]; Jason Matthews[2]; Henry Luten[3]; A. Michael Morrison[4]; Dianne Levermore[2]; [1]Georgia Institute of Technology, Molecular Design Institute; School of Chemistry and Biochemistry, School of Mats. Sci. and Eng., Atlanta, GA 30332 USA; [2]Georgia Institute of Technology, School of Chem. and Biochem., Atlanta, GA 30332 USA; [3]Microcoating Technologies, 3901 Green Industrial Way, Chamblee, GA 30341 USA; [4]Georgia Bureau of Investigation, c/o 2120 Iris Dr., Conyers, GA 30207 USA

The leading candidate for blue optoelectronic devices is GaN. One significant challenge in this materials system is reproducible, high level p-type doping. The main choice of most OMVPE researchers in this regard is Mg, supplied from Mg(Cp)2. This source suffers from high carbon incorporation in epilayers, and attempts to reduce the contamination levels often lead to significant quantities of hydrogen in the films. We have focused on new ligand platforms for Mg which have the potential to reduce the carbon incorporation problem. This lecture will cover the design of these new compositions, their preparation, purification and characterization, as well as preliminary data related to their employment in film growth studies. A new instrument has been developed for automated vapor pressure determination, and will be presented.

9:00 AM

Comparative Studies of AlGaN Grown by Trimethylaluminum (TMAl) and Tri-tertiarybutylaluminum (t-Bu3Al): Jung Han[1]; *Sean D. Donovan*[2]; Mary H. Crawford[1]; Jeff J. Figiel[1]; Michael A. Banas[1]; Michael E. Bartram[1]; Cammy R. Abernathy[2]; [1]Sandia National Laboratories, MS-0601, P.O. Box 5800, Albuquerque, NM 87185-0601 USA; [2]University of Florida, Dept. of Mats. Sci. & Eng., Rhines Hall, Gainesville, FL 32611 USA

The most commonly used Al precursor for OMVPE growth of AlGaN has been Trimethylaluminum (TMAl). It is known, however, that TMAl tends to react with ammonia (NH3) in the gas phase (adduct formation) causing a parasitic depletion of column-III reactants. Furthermore, it is known that the strong Al-C bond in TMAl molecules often leads to increased incorporation of carbon as an unintentional impurity. Triethylaluminum (TEAl) has been explored with only limited success; a very low vapor pressure at room temperature (0.03 Torr) greatly hinders its viability to be transported as a host element. Tri-tertiarybutylaluminum (t-Bu3Al) appears to be an attractive alternative for reasons such as a usable vapor pressure (~0.5 Torr) at room temperature, possibly a reduced Al-C bond strength, a larger molecule and therefore a reduced tendency of Louis acid-base adduct formation with NH3. In this paper we report the exploration of using t-Bu3Al as an alternative Al precursor for AlGaN growth. The extent of gas-phase parasitic reactions was evaluated by in-situ monitoring of the incorporation of column-III elements (as derived from growth rate measurements). Levels of various unintentional background impurities, such as carbon (C), oxygen (O), and silicon, in AlGaN were compared using SIMS. Preliminary investigation suggested a reduced C level in AlGaN grown with t-Bu3Al. To determine the usage of t-Bu3Al in device structures, we have grown AlGaN/GaN multiple quantum wells using both TMAl and t-Bu3Al. Comparable UV emission was observed by room temperature photoluminescence with both precursors. We will also report the electrical properties of AlGaN determined by Hall measurements. 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.

9:20 AM

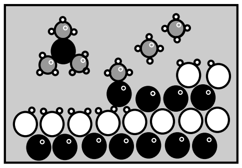
Gas Phase Thermal Decomposition of NH3 and TMG Study by In Situ Raman Spectroscopy: *Min Huang*[1]; [1]University of Florida, Dept. of Chem. Eng., Gainesville, FL 32611 USA

The gas phase thermal decomposition of NH3 and TMG in N2 has been studied at typical MOCVD reaction conditions by laser Raman spectroscopy. The reactions were probed in a vertical impinging flow cylindrical MOCVD reactor to simplify the analysis of the data. Concentration profiles of NH3 or TMG along the reactor centerline were monitored by measuring the ratio of the reactant or product species abundance to that of N2. Using N2 rotational spectra the temperature profile along the centerline was measured simultaneously. Measurements were also carried out below the decomposition temperature to estimate the diffusion coefficient. A model platform was developed to quantify the species diffusivities and reaction rate constants for an assumed mechanism from the measured concentration and temperature profiles. The model platform includes momentum, energy and species conservation equations, and incorporates an output least squares (OLS) inverse problem scheme for parameter identification or reactor optimization.

9:40 AM

Model Development of GaN MOVPE Growth Chemistry for Reactor Design: *Jingxi Sun*[1]; K. S. Boutros[2]; J. M. Redwing[2]; T. F. Kuech[1]; [1]University of Wisconsin, Dept. of Chem. Eng., 1415 Engineering Dr., Madison, WI 53706 USA; [2]Epitronics, 21002 North 19th Ave., Suite 5, Phoenix, AZ 85027 USA

Organometallic vapor phase epitaxy (OMVPE) of GaN involves high growth temperatures, gas phase pre-reactions, and subsequent gas flow complexity. In this study, computational fluid dynamics (CFD), combined with a direct comparison to



growth-based data, was used to determine the behavior of adduct and adduct-derived species within a high performance vertical MOVPE reactor. The growth chemistry model was increased in a step-wise fashion. At each step, the flow, temperature and concentration profiles are determined using available recent kinetic data. The influence of gas flow condition, temperature and the residence time on the distribution of adduct and adduct-derived species, and hence the GaN growth behavior was systematically investigated by computation and experiment. The oligimerization of adduct will affect the diffusion behavior above the growth surface, and hence the growth uniformity and growth rate. The uses of high speed inlets reduce the residence time and gas phase reactions leading to the improvement in growth uniformity and materials properties. Key design features identified in these studies to the design of GaN reactors will be presented.

10:00 AM BREAK

Monday, Morning, May 24, 1999
Session II
Non-Planar, Selective Growth Compliant Substrates

10:20 AM

Comprehensive Simulation of Planar Selective Area Growth Process and Nonplanar Epitaxy Using a 3D Vapor Phase Model: *Muhammad Ashraful Alam*[1]; [1]Lucent Technologies, Bell Laboratories, Rm. 2D-307E, 600 Mountain Ave., Murray Hill, NJ 07974 USA

A simple 3D vapor phase model is used to quantitatively interpret and clarify two widely used process techniques for integrated optoelectronic circuits. The first of these techniques is based on Selective Area Growth (SAG) process. In a SAG process, a set of oxide pads are deposited on the wafer. Since materials cannot grow on the oxide pads, the flow is modulated. By carefully choosing the geometry of the oxide pads, one can produce very complicated integrated circuits. We use an extensive set of experiments to verify the model and show how the model predicts both normal and anomalous profiles of thickness and composition including long range effects. We also give examples of three optoelectronic integrated circuits that are based on the predictions of the 3D vapor phase model. The second application involves the interpretation of nonplanar growth based on the vapor phase model. There are three key features of nonplanar growth none of which are currently well understood. First, the surface become more non-planar as growth continues; second, narrower mesas have higher growth rates; third, narrower channels have smaller growth rates. We provide a quantitative and consistent interpretation of all these features over a wide range of parameters to clarify the process dynamics involved in nonplanar growth.

10:40 AM

Shadow Masked OMVPE for Integrated Optical Structures Using a Micromachined Silicon Mask: *Greg M. Peake*[1]; Lei Zhang[1]; Nelson Li[1]; Andrew M. Sarangan[1]; Steve D. Hersee[1]; [1]University of New Mexico, Center for High Tech. Mats., 1313 Goddard SE, Albuquerque, NM 87106 USA

This paper describes the fabrication of micro-optical elements by shadow-masked, nonplanar OMVPE, using a novel, micromachined-silicon shadow mask. The micromachined mask is fabricated using deep-Si RIE and is robust, reusable and enables the fabrication of large nonplanar structures such as spherical GaAs microlenses. Direct fusion bonding has proven to be a convenient and reproducible method for mask placement on the host wafer. This new shadow mask technology has allowed the fabrication of 2D and 3D structures having smooth, nonplanar surfaces with no facetting, and we will compare this approach to the previously used epitaxial mask technology. We will also discuss the physical and optical properties of microlenses produced by this technique.

11:00 AM

Migration Effect on Semiconductor Surface for Narrow-Stripe Selective MOVPE: *Yasutaka Sakata*[1]; Keiro Komatsu[1]; [1]NEC Corporation, ULSI Device Dev. Lab., 2-9-1, Seiran, Otsu, Shiga 520-0833 Japan

The novel method for deriving the migration length (L_M) on a semiconductor surface, which is the most important parameter but has not been precisely investigated for narrow-stripe (NS) InP/InGaAsP selective-MOVPE, will be discussed. We found that the L_M can be deduced from the relationship between (111)B-facet length ($L_{(111)B}$) and (100)-facet length ($L_{(100)}$) in the edge-growth region formed at the side of SiO_2 masks. $L_{(111)B}$ and $L_{(100)}$ have linear relationship, therefore the L_M on (100) surface can be obtained from the extrapolation of $L_{(100)}$ at $L_{(111)B}=0$. Using this simple method, L_M was estimated to be a reasonable value of 2.1-mm for the growth temperature (T_g) of 650°C, the growth pressure of 100 hPa and the growth rate (R_g) of 1.45 mm/h. Furthermore, it is found that L_M increased with higher T_g (Ear R_g and longer-waiting time of pulse-mode epitaxy. The maximum L_M, the precursors' life-time and the diffusion coefficient were also estimated by the method from pulse-mode selective-MOVPE.

11:20 AM

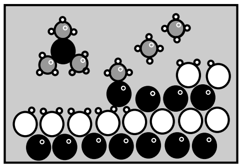
OMVPE Growth of Highly Mismatched InGaAs on Glass Compliant Substrates: *P. D. Moran*[1]; J. G. Cederberg[1]; D. M. Hansen[1]; R. J. Matyi[2]; T. F. Kuech[1]; [1]University of Wisconsin, Dept. of Chem. Eng., 1415 Engineering Dr., Madison, WI 53706 USA; [2]University of Wisconsin, Dept. Mats. Sci. and Eng., 1509 University Ave., Madison, WI 53706 USA

Three microns of highly mismatched (mismatch=3%) In0.40Ga0.60As has been grown on GaAs substrates, twist-bonded compliant substrates, and two types of glass-bonded compliant substrates for which the viscosity of the glass differ by five orders of magnitude. The compliant substrates consisted of a 10nm GaAs growth template bonded to a handle wafer. Quantitative high-resolution x-ray diffraction experiments have provided direct evidence of glass-bonded substrate compliance over macroscopic lateral dimensions. The highly mismatched films that are completely relaxed on both conventional and compliant substrates exhibit a strain distribution whose breadth is reduced from 270" when grown on the conventional substrate to 170" when grown on the glass-bonded compliant substrates. Atomic Force Microscopy has shown the films grown on the glass-bonded compliant substrates to exhibit an average surface roughness (~10nm) four times smaller than that of the film grown directly on a GaAs substrate (42nm).

11:40 AM

Growth of InGaAs Lattice-Mismatched Layers on GaAs and InP Compliant Substrates: *Koen Vanhollebeke*[1]; Ingrid Moerman[1]; Peter Van Daele[1]; Piet Demeester[1]; [1]University of Gent-IMEC, Dept. of Inform. Tech. (INTEC), Sint-Pietersnieuwstraat 41, Gent B-9000 Belgium

Thin GaAs compliant substrates have been developed in order to reduce the strain in lattice-mismatched layers during epitaxial overgrowth. Using OMVPE a variety of (30-80 Angstrom) thin GaAs layers were grown and successfully fused at 660°C on a host GaAs substrate with twist-angles between 10 and 35°. The resulting compliant substrates were overgrown with up to 2.2% lattice-mismatched and 600 nm thick InGaAs layers. Normarski phase contrast microscopy, photoluminescence and double crystal x-ray diffraction (DXRD) were used to characterize the heteroepitaxial layers. The smooth and cross-hatch free morphology and the reduced DXRD peakwidth of the heteroepitaxial layers indicate a substantial improvement of the quality of heteroepitaxial material using compliant substrates. Further research is underway to extend the concept and technique of compliant substrates to InP and other materials. The compliant substrates will be used for the fabrication of extended wavelength InGaAs-detectors for detection up to 2.5 mm.



Monday, Evening, May 24, 1999
Session III
In-Situ Monitoring & Characterization

7:00 PM

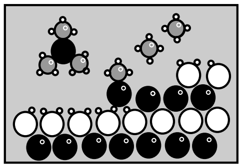
Variable Angle Surface Photoabsorption (SPA) of Deoxidation of III-V Wafers: Daniel Anthony Allwood[1]; *Nigel John Mason*[1]; [1]University of Oxford, Phys. Dept., Clarendon Lab., Oxford, Oxon OX1 3PU UK

Surface photoabsorption (SPA) is a simple optical technique for the in-situ monitoring of surfaces in atmospheric pressure semiconductor growth reactors involving the monitoring of the reflected intensity of p-polarised light. It has been used here to observe deoxidation of “epiready” GaAs wafers within a metalorganic vapour phase epitaxy (MOVPE) environment. At present, little is understood of the relevant oxide removal mechanisms, yet deoxidation is a process critical to the production of high quality, epitaxially grown structures. Variations in the sensitivity of SPA to the presence of the GaAs oxide are observed at different angles of incidence with the greatest sensitivity being demonstrated close to the Brewster angle of room temperature GaAs. Furthermore, variable angle SPA scans of deoxidised GaAs at temperatures between 20 - 700°C have allowed the Brewster angle and minimum (p-polarised) reflectivity to be estimated as a function of temperature. These data have been used to fit optical constants for “clean” GaAs at the temperatures considered, allowing temperature-dependent SPA signals from an oxide-covered GaAs surface to be calculated, using standard thin film theory. This modelled data shows good qualitative agreement with the SPA deoxidation traces obtained at different angles of incidence. The data presented here will allow the SPA monitoring of deoxidation to be performed quantitatively and, subsequently, for deoxidation mechanisms to be examined in greater detail than has previously been reported.

7:20 PM

Growth of (Al,Ga)InP-Based Laser Structure - Monitored by Realtime RAS: *Kolja Haberland*[1]; *Arnab Bhattacharya*[2]; Martin Zorn[1]; Markus Weyers[2]; Jörg-Thomas Zettler[1]; Wolfgang Richter[1]; [1]Technische Universität Berlin, Institut für Festköperphysik, Sekr. PN 6-1, Hardenbergstr. 36, Berlin D-10623 Germany; [2]Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH), Rudower Chausse 5, Berlin D-12489 Germany

Reflectance Anisotropy Spectroscopy, RAS, (also called Reflectance Difference Spectroscopy, RDS) is an ideal in-situ technique for growth-monitoring in MOVPE, applicable to most epitaxial systems with a high surface sensitivity. RAS permits to obtain information about surface stoichiometry and reconstruction, sample temperature, doping levels, layer thickness and composition non-destructively, in-situ and in real-time. Using a specially-designed spectrometer enabling combined RAS and reflectance measurements on rotating substrates in a commercial MOVPE reactor, we report the first full spectroscopic RAS-monitoring of the complete growth process for (Al,Ga)InP-based 650nm laser structures. First, a spectral data-base was built up from fundamental studies of (Al,Ga)InP RAS-signatures for different Al compositions, doping levels and growth temperatures coupled with experiments investigating GaAs/(Al,Ga)InP-interfaces. The latter permit a correlation of changes observed in the RAS spectra during laser growth with changes in doping levels, composition etc. The sensitivity of RAS makes it a particularly valuable monitoring tool in epitaxy of laser structures.



7:40 PM

Real-Time X-ray Scattering Studies of GaN Surface Structure and Growth Modes during OMVPE: *Jeffrey A. Eastman*[1]; Anneli Munkholm[2]; G. Brian Stephenson[1]; Orlando Auciello[1]; Carol Thompson[3]; Paul T. Fini[4]; Steven P. DenBaars[4]; James S. Speck[4]; [1]Argonne National Laboratory, Mats. Sci. Div., 9700 S. Cass Ave., Bldg. 212, Argonne, IL 60439 USA; [2]Argonne National Laboratory, Chem. Div., 9700 S. Cass Ave., Bldg. 433, Argonne, IL 60439 USA; [3]Northern Illinois University, Dept. of Phys., and Argonne National Laboratory, Mats. Sci. Div., DeKalb, IL 60115 USA; [4]University of California, Dept. of Mats., Bldg. 446, Santa Barbara, CA 93106 USA

We have carried out real-time studies of OMVPE growth of GaN using grazing incidence x-ray scattering at the Advanced Photon Source. We studied homoepitaxial growth on GaN(0001) thin-film substrates at temperatures up to 1050°C using trimethylgallium (TMG) and ammonia as precursors at a reactor pressure of 200 Torr. We observed intensity oscillations in the crystal truncation rods corresponding to layer-by-layer growth, which allowed the growth rate and growth mode boundaries to be determined as a function of process parameters. We found that the growth rate is temperature independent and TMG transport limited. The deposition rate at the step-flow to layer-by-layer boundary had an apparent activation energy of 3.0 eV. In addition, a new surface reconstruction with (sqrt{3} by 2 sqrt{3})R30 symmetry was observed at typical conditions for OMVPE growth. Its phase boundary was mapped as a function of temperature and ammonia partial pressure. A structural model for the reconstruction will be presented.

8:00 PM

In-situ Infrared Spectroscopy of Adsorbates during GaAs OMVPE: *J. Randall Creighton*[1]; Kevin C. Baucom[1]; [1]Sandia National Laboratories, P.O. Box 5800, MS-0601, Albuquerque, NM 87111 USA

We have used surface infrared spectroscopy (SIRS) to identify the adsorbates present on GaAs (001) during organometallic vapor phase epitaxy (OMVPE) and atomic layer epitaxy (ALE). The key advantage of SIRS, as compared to reflectance-difference spectroscopy (RDS) and related UV-vis reflectance techniques, is that the interpretation of infrared spectra is much more straightforward and less ambiguous. One example of the rich spectral information derived with SIRS is seen during the trimethylgallium (TMGa) ALE cycle. During the initial stages of TMGa exposure, methyl groups (CH3) bonded to both gallium and arsenic can be detected and differentiated. With time, the methyl-arsenic species disappear and methylene (CH2) species (the precursors to carbon incorporation) begin to cover the surface. During low-temperature OMVPE we also detect a significant methyl group coverage, and these results will be compared to the other in-situ optical measurements, e.g. RDS, at similar growth conditions.

8:20 PM

Integrated Real-Time QMS and Optical Techniques to Characterize and Control Growth in a Modified Commercial OMVPE Reactor: *K. A. Bell*[1]; M. Ebert[1]; S. D. Yoo[1]; D. E. Aspnes[1]; [1]North Carolina State University, Dept. of Phys., P.O. Box 8202, Raleigh, NC 27695 USA

We describe a growth analysis system that combines quadrupole mass spectrometry (QMS) with a high-speed, broadband, parallel-processing optical system that simultaneously performs spectroscopic ellipsometry (SE), kinetic ellipsometry (KE) and reflectance-difference spectroscopy (RDS) measurements. Both are integrated in a modified commercial OMVPE reactor. We use SE to determine layer thicknesses and average compositions, KE for near-surface compositions, and RDS to identify surface reconstructions. Optical data are obtained over a spectral range of 250-750 nm at a repetition rate of 1.6 Hz. Diode-to-diode noise is £ ±0.01%; spectra-to-spectra noise is £ ±0.15%. We use time-resolved QMS to identify gas-phase species and reaction byproducts during the deposition of and desorption from InP- and GaP-based materials. Synchronizing this information with changes in surface reconstructions obtained by RDS allows us to model surface chemistry and growth kinetics.

8:40 PM

In-situ Monitoring of Stress/Strain During AlGaN/GaN MOCVD: *Jung Han*[1]; Sean J. Hearne[1]; Eric Chason[1]; Jerry A. Floro[1]; Jeff J. Figiel[1]; John Hunter[1]; Hiroshi Amano[2]; [1]Sandia National Laboratories, P.O. Box 5800, MS-0601, Albuquerque, NM 87185-0601 USA; [2]Meijo University, Dept. of Electr. and Electri. Eng., Nagoya Japan

(Al, Ga, In)N family has been a subject of intense study for their wide applications in optoelectronic and electronic devices. As-grown nitride films are often found to be strained as determined by ex-situ characterizations such as x-ray diffraction, wafer curvature, PL and Raman measurements. Several mechanisms could contribute to and compound the occurrence of strain: (1) large mismatches (2.4% tension for AlN and 11% for InN on GaN) exist among these semiconductors with relatively small in-plane lattice constants, (2) relative high temperature (> 1000°C) growth on non-native substrates with substantial mismatches in thermal expansion, and (3) the employment of multi-step nucleation on LT buffer layers followed by island coalescence. It is thus desirable to isolate the strain effects during and after the growth. In this talk we describe an in-situ real time monitoring of stress evolution during OMVPE of (Al, Ga)N on sapphire using a wafer-curvature-based stress monitor. In spite of the 16% compressive lattice mismatch of GaN to sapphire, we find that GaN consistently grows in tension (with a tensile stress of 0.2~0.5 Gpa) at 1050^{o}C. The origin of this tension is still under investigation. In-situ stress monitoring indicates that there is no measurable relaxation of the tensile growth stress during annealing or thermal cycling. Depending on the LT buffer layers employed, GaN films can be nucleated under either a tensile or compressive condition. The combination of in-situ (wafer-curvature) stress monitoring and ex-situ stress determination (from high-resolution x-ray diffraction) provides an accurate measurement of the magnitude of thermal expansion mismatch between GaN and sapphire substrates. 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.

Tuesday, Morning, May 25, 1999
Session IV
Nitrides Growth

8:20 AM

The Influence of OMVPE Growth Pressure on the Morphology, Compensation, and Doping of GaN and Related Alloys: *Alma Estes Wickenden*[1]; Daniel D. Koleske[1]; Richard L. Henry[1]; Robert J. Gorman[1]; Mark E. Twigg[1]; Jaime A. Freitas[1]; W. James Moore[1]; [1]Naval Research Laboratory, Elect. Sci. & Tech. Div., Code 6800, 4555 Overlook Ave., S.W., Washington, DC 20375 USA

Requirements for nitride high-power microwave devices mandate highly resistive isolation layers, high quality p/n junctions, high mobility, and low trap density. We have determined that OMVPE growth pressure profoundly influences the morphology, dopant incorporation, compensation level, growth rate, and alloy composition of GaN and AlGaN. High pressure growth of both the nucleation layer and the epitaxial layer yields larger grain size and electron conduction in unintentionally-doped GaN films. Increased pressure also reduces compensation and increases electron mobility in GaN:Si films. GaN:Mg films grown under conditions of increasing pressure or dopant flow show stronger Mg-related recombination intensity in PL experiments, which will be compared to SIMS and Hall data. Possible pressure-related compensation mechanisms for doped and HR-GaN, related either to grain boundaries or point defects in the films, will be discussed. AlGaN films must be grown at reduced pressure. Transport characteristics of HEMT structures on HR-GaN grown at varying pressures will be compared.

8:40 AM

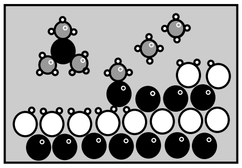
SIMS Investigations into the Effect of Growth Conditions on Residual Impurity Incorporation in GaN and $Al_xGa_{1-x}N$: *Giacinta Parish*[1]; Stacia Keller[1]; Umesh K. Mishra[1]; Steven P. DenBaars[2]; [1]University of California, Dept. of Electr. and Comp. Eng., Santa Barbara, CA 93106 USA; [2]University of California, Dept. of Mats. Eng., Santa Barbara, CA 93106 USA

Residual impurities in GaN and AlGaN have long an important issue pertaining to the quality of epitaxial films obtainable. They have been linked to both deep and shallow levels and, in addition to their contribution to background carrier levels, affect many other optical and electronic properties of the materials. The source of these impurities has to date been a subject of speculation. In this study we investigated the role of growth conditions in residual impurity incorporation. Secondary Ion Mass Spectrometry (SIMS) depth profile analysis was executed on GaN and AlGaN wafers with multiple layers in which temperature, growth rate, V/III ratio and doping (with Si) were varied. Trends in oxygen, carbon and silicon concentrations were studied as a result of these variations in growth conditions. In most cases similar trends were observed for GaN as for AlGaN. Growth temperature and V/III ratio had the largest effect on impurity concentrations. The silicon incorporation was less susceptible to growth conditions than that of oxygen and carbon.

9:00 AM

OMVPE Growth of AlGaN/GaN for Ultraviolet Emitters: *Jung Han*[1]; Mary H. Crawford[1]; Randy J. Shul[1]; Jeff J. Figiel[1]; Steve R. Lee[1]; Mike A. Banas[1]; Y. K. Song[2]; Arto V. Nurmikko[2]; [1]Sandia National Laboratories, MS-0601, P.O. Box 5800, Albuquerque, NM 87185-0601 USA; [2]Brown University, Div. of Eng., Providence, RI 02912 USA

AlGaN/GaN based ultraviolet (UV) emitters have received relatively little attention when compared with the InGaN-based visible optoelectronics. They are nevertheless attractive for potential applications such as illumination (as a white-light source) and chemical sensing. Several issues/problems have been identified early on: optical efficiency from an indium-free GaN quantum well (QW) is speculated to be much less than its InGaN counterpart, highly conducting p-doping of AlGaN (by Mg) has not been convincingly reproduced, and growth of AlGaN/GaN heterostructures on sapphire tends to create excessive tensile strains leading to cracking, to just name a few examples. In this paper we intend to address these subjects as building blocks for fabricating compact UV light emitters. An attempt to control strain relaxation and suppress cracking associated with AlGaN epilayers using various buffer layer schemes will be presented. Furthermore, emission efficiency of AlGaN/GaN QWs will be presented as functions of growth parameters. It is observed that growth pressure could exert a strong influence on the optical efficiency; an order of magnitude improvement in efficiency can be obtained when the pressure is increased from 40 to 80 Torr. While these issues are subjects of ongoing research in our laboratory, we have fabricated GaN and AlGaN multiple QW p-n junction diodes to test the feasibility of light emission from indium-free QW LEDs. Emission wavelengths of 353 and 335 nm were observed from GaN and AlGaN QWs, respectively. We will also compare the device performance of GaN-based QW UV LEDs with isoelectronic dopings such as Al and In in the active region. 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.



9:20 AM

Growth Conditions and Their Effect on Hall Mobility and Persistent Photoconductivity of Undoped GaN: *Wen Wang*[1]; Soo Jin Chua[1]; Gang Li[1]; [1]Institute of Materials Research and Engineering, Opto-electronics and Photonics, 10 Kent Ridge Crescent (NUS) 119260 Singapore

Growth conditions have been widely optimized to improve the Hall mobility of undoped GaN. The electron density was in the order of mid-1016 cm-3 and the Hall mobility varied from < 50 cm2/sV to > 500 cm2/sV. Temperature-variable Hall effect measurements were used to investigate their electrical properties. We found that the polar phonon scattering determines the Hall mobility of high quality GaN at high temperatures, while very strong ionized impurity scattering limits the Hall mobility of low quality GaN at low temperatures. Illumination at low temperatures can persistently increase the Hall mobility but has little effect on the electron density of low quality undoped GaN. The induced persistent photoconductivity (PPC) effect was temperature dependent and its transient properties were therefore analyzed at different temperatures. The origin of intrinsic defects responsible for the ionized impurity scattering and its relationship with the Hall mobility, PPC effect and the growth conditions will be discussed.

9:40 AM

Characterization of Undoped and Silicon-Doped InGaN/GaN Single Quantum Wells: *Bernd G. Schineller*[1]; Peng Huei Lim[1]; Gennadii P. Yablonskii[2]; Evgenii V. Lutsenko[2]; Oliver Schoen[3]; Harry Protzmann[3]; Michael Heuken[3]; Klaus Heime[1]; [1]RWTH-Aachen, Institut fuer Halbleitertechnik, Templergraben 55, Aachen, NRW D-52056 Germany; [2]Belaurs Academy of Sciences, Institute of Physics, F. Skaryna av. 70, Minsk 220072 Belarus; [3]AIXTRON AG, Process Technology, Kackertstr. 15-17, Aachen, NRW D-52072 Germany

We investigated the influence of doping and InGaN layer thickness on the emission intensity, spectral purity and line position of InGaN/GaN double heterostructures and single quantum wells (SQW) of thicknesses between 1.25 and 50 nm by temperature and intensity resolved photoluminescence (PL). The crystalline quality and composition of the InGaN active layer and the GaN claddings were assessed by high resolution x-ray diffraction. For material with emission wavelengths up to 450 nm only a small percentage of the volume exhibited phase separation and typical PL linewidths were between 50 and 100 meV. SQW with active layer thicknesses of 2.5 nm were found to be most efficient, yet quantization effects and piezoelectric fields appear. The amount of field screening due to homogenous or d-doping with silicon will be discussed and results on the influence of the InGaN layer thickness on the crystalline quality of the surrounding GaN cladding will be presented.

10:00 AM BREAK

Tuesday, Morning, May 25, 1999

Session V

Growth and Doping Mechanisms

10:20 AM

Effects of Dopants on Step Structure and Ordering in GaInP: *Gerald B. Stringfellow*[1]; R. T. Lee[1]; S. W. Jun[1]; [1]University of Utah, College of Eng., Office of the Dean, 1495 E. 100 S. Rm. 214 KRC, Salt Lake City, UT 84112-1109 USA

High concentrations of n- and p-type dopants are well-known to lead to the elimination of the (111) superlattice structure formed due to CuPt ordering during OMVPE growth. However, the reason for the growth of disordered material when high concentrations of dopants are present remains unclear. Our earlier work showed that the concentrations of the donor Te leading to the reduction in the degree of CuPt order also lead to dramatic changes in the step structure. The effect was ascribed to the surfactant nature of Te, which is believed to segregate at the surface and, particularly, to collect at the {110} step edges. This paper compares the results obtained for three other dopants, Zn, Si, and Mg, to those obtained for Te. The degree of order was determined from the bandgap energy determined using low temperature photoluminescence spectroscopy and the ordered structure was characterized using transmission electron microscopy. The surface structure measured using atomic force microscopy. Both Zn and Si produce disordering at concentrations of approximately 1018 cm-3, similar to those required for Te. However, neither Si nor Zn produces a change in the step structure. Mg doping has been limited to values too low to produce disordering. However, it has a marked effect on the step structure - leading to step bunching. The hindrance of step motion caused by Mg produces 2 variants of the CuPt structure for growth on vicinal substrates, whereas only 1 variant is produced in the undoped layers. This is due to 2 dimensional nucleation on the terraces between steps.

10:40 AM

Selective Incorporation of Si Along Step Edges During Delta-Doping on OMVPE-Grown GaAs (001) Vicinal Surfaces: *Junichi Motohisa*[1]; Chiharu Tazaki[1]; Tomoki Irisawa[1]; Takashi Fukui[1]; [1]Hokkaido University, Research Center for Interf. Quantum Elect., North 13, West 8, Sapporo, Hokkaido 060-8628 Japan

Atomic-scale control of the incorporation sites of impurity atoms in semiconductors is important for the fabrication of ultimate nano-scale devices. We will report on the delta-doping of Si using SiH4 on OMVPE-grown GaAs (001) vicinal surfaces to explore the possibility of selective incorporation of Si along atomic steps, and to realize doping quantum wires, which we proposed to form by the combination of multiatomic steps and the wire-like doping. We have found that the doping density on vicinal surfaces is enhanced as the misorientation angle is increased, which suggests the enhanced decomposition of SiH4 and the selective incorporation of Si at step edges. It is also found that this selective incorporation can be enhanced by the annealing of the surface prior to the delta-doping. The effect of doping conditions such as temperature and doping density will also be discussed in terms of enhancement ratio which represents the amount of incorporation at the step regions relative to the terrace regions.

11:00 AM

Unusual Memory Effect for Te Doping of GaInP: *Sarah R. Kurtz*[1]; Bob Reedy[1]; [1]National Renewable Energy Laboratory, MS3212, 1617 Cole Blvd., Golden, CO 80401 USA

Diethyltellurium has been used as a dopant source for Te doping of III-Vs. Growth conditions that result in 2 X 10^{18} electrons/cm^3 for a 1-mm-thick layer of GaInP give an order of magnitude fewer electrons when duplicated for a thin (0.09-mm-thick) GaInP layer. This “memory” effect complicates the growth of devices that require thin, doped layers. Attempts to overcome this "memory" problem by flowing Te just before initiating growth of the GaInP were unsuccessful. Surprisingly, the effect persisted even when the thin GaInP layer was grown on a Te-doped GaAs layer. The effect was reversed by flowing Te during a 5-min stop growth after growth of 0.01 mm of GaInP. The data are not trivially explained by Te surface segregation. SIMS and CV data will be presented to characterize the data more quantitatively and pursue the possibility that the surface structure is both affected by and affects the incorporation of tellurium in GaInP.

11:20 AM

Surface Phases of InP and InGaP (001) in the Organometallic Vapor Phase Epitaxy Environment: *Robert F. Hicks*[1]; Lian Li[1]; Byung-Kwon Han[1];

Daniel C. Law[1]; Qiang Fu[1]; Connie H. Li[1]; [1]University of California, Los Angeles, Chem. Eng. Dept., 5531 Boelter Hall, Los Angeles, CA 90095 USA

Indium phosphide on InP (001) and indium-gallium phosphide on GaAs (001) was grown by organometallic vapor phase epitaxy (OMVPE). After growth, the atomic composition and structure of the surfaces were characterized by scanning tunneling microscopy, x-ray photoemission, and vibrational spectroscopy. Indium phosphide (001) exhibits two structures, the (2x1) and (2x4). The (2x1) is formed at V/III ratios greater than 20 and consists of a complete layer of buckled phosphorous dimers. The dangling bonds on these dimers are reactive, and during growth become covered with hydrogen and tertiarybutyl ligands. Below a V/III ratio of 20, a (2x4) reconstruction is observed, which is terminated with a mixture of indium and phosphorous dimers. These dimers are less reactive than those on the (2x1), but do become partially covered with adsorbates during growth. New reconstructions are recorded on InGaP (001) films that are induced by strain. These also will be described at the meeting.

11:40 AM

The Surface Structure of Arsine-Annealed Ge(100) and Implications for Heteronucleation of GaAs: *J. M. Olson*[1]; W. E. McMahon[1]; [1]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CA 80401 USA

While much is known about the Ge(100) surface in a UHV/MBE environment, little has been published about this surface in an MOCVD environment. Using scanning tunneling microscopy, Auger electron spectroscopy and low energy electron diffraction, we show that arsine-treated surfaces are distinctly different from those treated with As4 in an MBE environment. Most importantly, arsine etches Ge. This precludes the development of a simple 1x2 surface reconstruction with well ordered steps. Instead, the arsine-treated Ge(100) surface is composed of a mixture of 1x2 and 2x1 reconstructed terraces accompanied by significant step bunching. Time-dependent reflectance difference measurements show that the transition rate from an As-terminated (1x2) terrace reconstruction to a stable arsine-annealed surface is a function of the substrate temperature, substrate miscut from (100) and arsine partial pressure, and, for typical prenucleation conditions, is relatively slow. These results explain many of the empirically derived GaAs nucleation conditions that have been published previously.

Tuesday, Evening, May 25, 1999

Session VI

Nitrides: Selective & Lateral Overgrowth

7:00 PM

Time Evolution of LEO GaN Morphology: *James P. Ibbetson*[1]; Hugues Marchand[1]; Paul T. Fini[2]; Steven P. DenBaars[2]; James S. Speck[2]; Umesh K. Mishra[1]; [1]University of California, Santa Barbara, Dept. of Elect. and Comp. Eng., Santa Barbara, CA 93106 USA; [2]University of California, Santa Barbara, Dept. of Mats., Santa Barbara, CA 93106 USA

Recently, lateral epitaxial overgrowth (LEO) of GaN has generated extensive interest due to the low dislocation density attainable in the overgrown material. Here we report on a scanning electron microscopy study of the time evolution of LEO stripes grown from patterned SiO2/GaN/Al2O3 substrates. The aim of the study is to help understanding the mechanisms of facet formation and the lateral growth rates, which depend strongly on growth conditions and pattern orientation. Such issues are important to obtain high quality coalescence of adjacent LEO regions to form quasi-substrates, for example. The data fit well with a kinetics-based picture of growth in which the relative growth velocities of different facets are determined by their relative reactivities and surface areas, while the volume deposition rate remains constant. The effects of different growth conditions can then be explained as changing the relative reactivities of the facets, with qualitative agreement between experiment and the ideal bond configuration of the observed facets. One important consequence is that the lateral growth rate decreases as the LEO surface area increases.

7:20 PM

Transport Limitations in Epitaxial Lateral Overgrowth of Gallium Nitride: *Michael E. Coltrin*[1]; *Michael E. Bartram*[1]; *Christine C. Willan*[1]; *Jung Han*[1]; [1]Sandia National Laboratories, Dept. 1126, MS 0601, Albuquerque, NM 87185 USA

In Epitaxial Lateral Overgrowth (ELO) of GaN, 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. Growth proceeds from the exposed regions vertically and laterally, over-growing the dielectric mask. We have studied the kinetics of GaN ELO through systematic variation of the masked and exposed area dimensions. A 2-D gas-phase diffusion model was developed which shows that (1) transport limitations strongly affect the rate of coalescence of the growing ELO films; (2) growth rates change continuously throughout the ELO coalescence; (3) the V/III ratio at the growth surface, which affects the ratio of lateral to vertical growth rates, also changes continuously throughout coalescence. Model predictions are verified by SEM analysis of grown films.

7:40 PM

Lateral Epitaxial Overgrowth of GaN by OMVPE: A Comparison of Trimethyl Gallium and Diethyl Gallium Chloride Sources: *L. Zhang*[1]; D. M. Hansen[1]; K. A. Dunn[2]; S. E. Babcock[2]; T. F. Kuech[1]; [1]University of Wisconsin, Dept. of Chem. Eng., 1415 Engineering Dr., Madison, WI 53706 USA; [2]University of Wisconsin, Dept. of Mats. Sci., 1500 Engineering Dr., Madison, WI 53706 USA

Lateral overgrowth epitaxial (LEO) of GaN was investigated using trimethyl gallium (TMGa) and diethyl gallium chloride (DEGaCl) sources under comparable growth conditions in a MOVPE reactor. DEGaCl allows for the development of the hydride vapor phase epitaxy growth conditions near the growth front allowing for high lateral growth rates. SEM, TEM and AFM have been used to characterize the facet information, surface morphology and defect structure. High growth temperatures and high V/III ratios result in higher lateral growth rate for openings aligned along the <1-100> direction and vertical and sloped facets can be produced by changes in the reactor operating conditions. The DEGaCl leads to smoother, less jagged facets when compared to TMGa-based growth. Jagged facets lead to a high defect density at the point of coalescence, as revealed by TEM. LEO GaN using DEGaCl source has smaller kink density, favorable for fast and smooth coalescence under conditions of a high V/III ratio required for improved materials properties. The different in LEO behavior for the two Ga sources is discussed in terms of the chloride-based growth chemistry and existing models of HVPE growth.

8:00 PM

Mechanisms for Lateral Growth and Coalescence in GaN SAG: *Michael E. Bartram*[1]; Michael E. Coltrin[1]; Christine C. Willan[1]; Nancy Missert[1]; Mary H. Crawford[1]; Jung Han[1]; Albert G. Baca[1]; [1]Sandia National Laboratories, Dept. of Chem. Proc. Sci., MS 0601, Albuquerque, NM 87185-0601 USA

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 step-flow 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 evolving to meet the upper most surface of the initial growth features. The step-flow 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. Uniform cathodoluminescence (CL) data suggest that this mechanism, with crystal growth being initiated at a single point at the convergence line of adjacent features, can influence materials properties significantly.

8:20 PM

Growth and Characterization of AlGaN/GaN Heterostructures by Selective-Area Lateral Epitaxial Overgrowth on Sapphire Substrates: Christopher J. Eiting[1]; Damien J. H. Lambert[1]; Ho-Ki Kwon[1]; *Russell D. Dupuis*[1]; Zuzanna Lilental-Weber[2]; Jamie A. Freitas[3]; [1]The University of Texas at Austin, Microelectronics Research Center, PRC/MER 1.608C-R9900, Austin, TX 78712-1100 USA; [2]Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., MS 62-203, Berkeley, CA 94720 USA; [3]Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC 20375 USA

Data are presented on the growth and properties of GaN and AlGaN films on sapphire substrates using selective-area lateral epitaxial overgrowth (SALEO) by low-pressure metalorganic chemical vapor deposition. The GaN lateral growth rate and surface morphology are found to depend upon the growth temperature and V/III ratio and is strongly dependent upon stripe orientation. Two-step SALEO growth results in improved materials with reduced dislocation density. The films have been characterized by photoluminescence (PL), cathodoluminescence (CL), X-ray diffraction, atomic-force microscopy (AFM), micro-Raman and micro-PL characterization, and transmission electron microscopy (TEM). The CL spectra (at 4K and 300K) and spatial intensities of the CL emission for SALEO films is correlated with the mask position with the brightest emission arising near the mask. We believe this is due to partial decomposition of the mask materials and subsequent doping of the nitride film. Comparison of SALEO films grown with various mask materials, e.g., Si3N4, will be presented to effect a reduced background doping in the SALEO film, as expected for the more chemically stable masks. TEM analysis and AFM characterization of the GaN and AlGaN/GaN heterostructures indicates a low threading dislocation density for SALEO films with some dislocation loops present. A study of the performance of AlGaN/GaN heterostructures grown on SALEO substrates will be presented.

8:40 PM

Nanoheteroepitaxy: Selective MOCVD Growth of GaN on Compliant, Nanostructured SOI: *David Zubia*[1]; Saleem Zaidi[1]; Steven J. Brueck[1]; Stephen Derek Hersee[1]; [1]University of New Mexico, Center for High Tech. Mats., 1313 Goddard, SE, Albuquerque, NM 87106 USA

We have studied the selective area growth of GaN on a two-dimensional array of compliant nanosized Si(111) mesas fabricated on SOI. This technique, which we call nanoheteroepitaxy, exploits state-of-the-art lithography to pattern nanoscale (10 -100 nm) islands on the surface silicon layer of a <111> SOI wafer. Selective epitaxial growth is then performed and the epilayer nucleates as an array of nanoscale islands with a truncated prismatic shape. The nanoscale islands are mechanically isolated from each other and are small enough to undergo 3-dimensional stress relief mechanisms that are not available in conventional (planar) heteroepitaxy. The theory of nanoheteroepitaxy (which has been submitted for publication) predicts that very large mismatch strains can be accommodated without the creation of mismatch defects. This paper will briefly discuss the theoretical basis for nanoheteroepitaxy, the growth habit for GaN (including nucleation and coalescence) and the materials properties of GaN grown using this novel approach.

9:00 PM

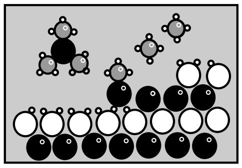
InGaN/GaN Quantum Wells Grown on V-Grooves of Epitaxial Lateral Overgrown GaN: *Xingang Zhang*[1]; P. D. Dapkus[1]; J. T. Kobayashi[1]; N. P. Kobayashi[1]; In Kim[2]; D. H. Rich[3]; [1]University of Southern California, Compound Semiconductor Laboratory, Dept. of Mats. Sci., 3651 Watt Way, VHE313, Los Angeles, CA 90089 USA; [2]University of Southern California, Dept. of Electr. Eng./ Electr. Phys., SSC512, Los Angeles, CA 90089 USA; [3]University of Southern California, Dept. of Mats. Sci., Photonic Materials and Device Laboratory, VHE 607, Los Angeles, CA 90089 USA

InGaN/GaN quantum wells (QW) were grown on V-grooves of lateral epitaxial lateral overgrown (ELO) GaN using sapphire (0001) substrate and SiNx mask by metalorganic chemical vapor deposition (MOCVD). SEM, cathodoluminescence wavelength imaging measurements (CLWI) show that the In composition of the QW on the top of ELO GaN V-grooves is much higher than that on the side wall, indicating that the In atoms have strong tendency to migrate to the top of the V-grooves during the QW growth. This tendency is reduced when the V/III ratio is reduced. The effects of V/III ratio, growth temperature as well as stripe orientation on the In incorporation and the optical properties of QW were also studied. Possible mechanisms are discussed. Our observance strongly indicates the potential realization of new low dimensional III-Nitride photonic devices.

9:20 PM

Tungsten Masking for Selective Area Growth of Al(x)GaN(1-x) on Sapphire: *Christine C. Willan*[1]; Michael E. Bartram[1]; Jung Han[1]; James G. Fleming[1]; Mary H. Crawford[1]; Nancy A. Missert[1]; Albert G. Baca[1]; Jeff J. Figiel[1]; Michael A. Banas[1]; [1]Sandia National Laboratories, Dept. of Mats. Proc. Sci., 1126, MS 0601, P.O. Box 5800, Albuquerque, NM 87185-0601 USA

Successful lateral over-growth of MOCVD AlxGa(1-x)N has been achieved using a tungsten mask. This suggests the limited growth conditions imposed by conventional masks (SiO2 or Si3N4) can be expanded considerably to apply the advantages of selective area growth (SAG) for AlGaN CVD. Lack of nucleation on tungsten facilitates incorporation of higher Al percentages in AlGaN. This allows the lattice constant to be varied, providing greater flexibility to tune the band gap for ultraviolet emission. The SAG of AlGaN was demonstrated using a tungsten pattern having a series of adjacent SAG regions in which both the masked and unmasked areas were varied systematically on a single substrate. Coalesced films were achieved, but film quality was reduced by the growth of AlGaN on tungsten in some regions. Scanning electron microscopy (SEM) revealed that these features were a direct result of AlGaN nucleation on the underlying GaN buffer layer via sub-micron cracks in the tungsten mask. In the absence of cracking, AlGaN nucleation did not occur on tungsten as verified by surface analysis measurements. Photoluminescence measurements of coalesced SAG regions revealed both band edge (325 nm) and deep level (510 nm) emission that were shifted spectrally from that of a non-SAG control region on the same substrate. In addition, cathodoluminescence (CL) and transmission electron microscopy (TEM) characterization of AlGaN SAG films using a refined tungsten process will be presented. (Work performed at Sandia National Laboratories under DOE contract DEAC04 94AL85000.)



Wednesday, Morning, May 26, 1999
Session VII -
Devices I

8:20 AM

Growth of Highly Strained 1.2 um GaInAs/GaAs Quantum Wells for Long-Wavelength Lasers: *Dietmar Schlenker*[1]; Tomoyuki Miyamoto[1]; Zhibiao Chen[1]; Fumio Koyama[1]; Kenichi Iga[1]; [1]Tokyo Institute of Technology, Precision and Intelligence Laboratory, 4259 Nagatsuta, Midori-ku, Yokohama-shi, Kanagawa-ken 226-8503 Japan

In this paper we show that highly strained GaInAs/GaAs quantum wells of good quality can be grown by LP-MOVPE using tertiarybutylarsine. Usually, a transition from 2D to 3D growth mode is observed for the growth of highly strained layers, but we eliminated this transition by employing special growth techniques. A strained buffer layer structure was used to remove dislocations which trigger 3D growth. The surface migration length was controlled by optimizing growth temperature and V/III ratio to prohibit the incorporation of migrating indium atoms into indium rich islands. Photoluminescence wavelengths of up to 1.2um with a FWHM of 23meV were achieved. Mapping out the critical thickness of GaInAs/GaAs layers by photoluminescence measurements we found no observable quality degradation for thickness even exceeding those calculated based on the Matthews and Blakeslee method, but our results fit the People and Bean model very well. Lasing up to 1.165um can be achieved with a threshold current density of 210A/cm2.

8:40 AM

Development of $Ga_{0.51+x}In_{0.49-x}P/Ga_yIn_{1-y}As$ Tandem Solar Cells Grown by MOVPE: *Frank Dimroth*[1]; Andreas W. Bett[1]; Peter Lanyi[1]; Ute Schubert[1]; [1]Fraunhofer Institute for Solar Energy Systems ISE, SWT, Oltmannsstr. 5, Freiburg, Baden-Wuerttemberg 79100 Germany

We investigated the growth of GaInP, GaAs and GaInAs solar cell structures on an AIX2600-G3 multiwafer MOVPE reactor with a capacity of 5 times 4" substrates. The aim of this work is the development of lattice-matched GaInP/GaAs and GaInP/GaInAs tandem solar cells for space and terrestrial concentrator applications. Theoretical calculations predict a higher tandem conversion efficiency for the second approach. The main problem of this structure is, that it can not be grown lattice-matched to GaAs or Ge substrates. Therefore, we investigated the growth of different In-graded buffer layers on GaAs. Resulting GaInAs solar cells have very high external quantum efficiencies. The quantum efficiency in the spectral range between 300 and 900 nm is nearly equal to comparable GaAs solar cells. The AM1.5g efficiency of the best $Ga_{0.82}In_{0.18}As$ cell with an absorption edge at 1050 nm was 20.4 % (cell area = 1 cm^2). Solar cells with optimised antireflection coatings are under development.

9:00 AM

The Growth of InGaAsN for 1.0 eV Solar Cells Lattice Matched to GaAs: *Andrew A. Allerman*[1]; Steven R. Kurtz[1]; Eric D. Jones[1]; James M. Gee[1]; Steven A. Ringel[2]; Daewon Kwon[2]; Robert J. Kaplar[2]; J. J. Boeckl[2]; [1]Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185 USA; [2]The Ohio State University, Dept. of Elect. Eng., 2015 Neil Ave., Columbus, OH 43210 USA

Multi-junction tandem solar cells are being developed as power sources for satellites. Models indicate that record efficiencies (>40%) would be obtained for tandem cells where a 1.05eV bandgap cell is added in series to proven InGaP-GaAs tandem structures. The growth by metal-organic chemical vapor deposition and performance of In0.07Ga0.93As0.98N0.02 solar cells, with 1.05eV bandgap, lattice matched to GaAs is described. Post growth thermal annealing was found to significantly improve the photoluminescence from bulk films, reduce trap densities as measured by Deep Level Transient Spectroscopy and improve the internal quantum efficiencies of solar cells. The hole diffusion length in annealed, n-type InGaAsN is 0.6-0.8µm, and solar cell internal quantum efficiencies >70% are obtained. Electron diffusion lengths remain negligible (0.1µm. Optical studies indicate that defects or impurities, from InGaAsN doping and nitrogen incorporation, limit solar cell performance. 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.

9:20 AM

MOVPE Growth Investigations of (GaIn)(NAs)/GaAs Quantum Well Structures: *Falko Höhnsdorf*[1]; Jörg Koch[1]; Simone Leu[1]; Christoph Ellmers[1]; Martin Hofmann[1]; Wolfgang W. Rühle[1]; Wolfgang Stolz[1]; [1]Philipps-University, Mats. Sci. Center and Dept. of Phys., Hans-Meerwein-Str, Marburg D-35032 Germany

The interest in the material system (GaIn)(NAs)/GaAs has been increasing in recent years due to the large bowing parameter of the bandgap energy, which allows the realization of 1.3µm and 1.55µm light emitting structures based on GaAs substrates. In this study the incorporation of N and In into (GaIn)(NAs)/GaAs-MQW grown using the group-V precursors tertiarybutylarsine (TBAs) and 1, 1-Dimethylhydrazine (UDMHy) is investigated by means of high-resolution X-ray diffraction (XRD) in combination with XRD simulations. Quaternary (GaIn)(NAs) wells with high concentrations of In up to 40% and of N up to 10% have been realized both lattice matched as well as strained on GaAs. Under optimized growth conditions the high structural perfection is manifested by narrow XRD linewidths reaching the theoretical limit for the respective MQW structures. These growth optimizations lead to an improvement of the optical quality of the MQW layers yielding an optical pumped 1.3µm-VCSEL-structure at room temperature with a laser threshold comparable to conventional (GaIn) As/GaAs VCSEL structures.

9:40 AM

The Growth and Design of Vertical External Cavity Lasers for Intra-Cavity Frequency Doubling: *Andrew A. Allerman*[1]; Mary H. Crawford[1]; W. Joe Alford[1]; Thomas D. Raymond[1]; [1]Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185 USA

Intra-cavity frequency doubling employing a Vertical External Cavity Surface Emitting Laser (VECSEL) and a non-linear crystal with a dielectric mirror is being explored as a compact, milliwatt-level blue-green source. The VECSEL consists of a conventional GaAs-AlAs DBR mirror with a 10-15 period compressively strained GaAsP-InGaAs-AlGaAs active region. The InGaAs quantum wells are separated by 0.5 wave spacers to from a resonant, periodic gain structure. Optimization of the structure and the growth by metal-organic chemical vapor deposition of the quantum well active region will be described. This optimization has resulted in over 200mW in output power at 980nm with a 25% conversion efficiency of the 800nm optical pump. The addition of a KNbO3 non-linear crystal with an integrated dielectric output coupler has produced 5mW of output power at 490nm with a 330mW of pump power resulting in a pump-to-blue conversion efficiency of 1.5%. 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.

10:00 AM BREAK

Wednesday, Morning, May 26, 1999

Session VIII

MID-IR Materials and Devices

10:20 AM

The Growth of InPSb/InAsSb Strained-Layer Superlattices for Use in Infrared Emitters: *Robert M. Biefeld*[1]; Steven R. Kurtz[1]; [1]Sandia National Laboratories, Dept. 1113, MS 0601, P.O. Box 5800, Albuquerque, NM 87185 USA

We are continuing to explore the growth by metal-organic chemical vapor deposition (MOCVD) of novel mid-infrared (3-5 µm) infrared emitters (lasers and LED's) for use in infrared emitters and chemical sensor systems. As-rich, InAsSb heterostructures display unique electronic properties that are beneficial to the performance of these midwave infrared emitters. Previously we have made gain-guided, injection lasers using not intentionally doped, p-type AlAs0.16Sb0.84 for optical confinement and both strained InAsSb/InAs MQW and InAsSb/InAsP strained-layer superlattice (SLS) active regions. We have also reported the first ten-stage cascaded lasers and LED's with type I InAsSb/InAsP quantum-well active regions grown by MOCVD. These cascaded lasers employ a (p) GaAsSb/ (n) InAs semimetal electron/hole source between stages. In compressively strained InAsSb SLSs, it is necessary to maximize the light-heavy (|3/2,±1/2> - |3/2,±3/2>) hole splitting to suppress non-radiative Auger recombination. We are currently exploring the growth of new emitter structures as well as the use of novel materials in these structures in an attempt to further reduce the Auger recombination by increasing the hole confinement using InPSb. We will describe the MOCVD growth of InP1-xSbx layers, and InAsSb/InPSb SLS active regions for use in mid-infrared emitters. These materials were grown in a high speed rotating disk reactor. By changing the layer thickness and composition of InAsSb/InPSb SLSs, we have prepared structures with low temperature (<20K) photoluminescence wavelengths ranging from 3.4 to 4.8 µm. Initial quantum confinement data indicate that there is about a factor of two greater in the valence band offset for InPSb than for InAsP and InAsSb. Results for devices fabricated from these new structures and materials will be presented as they become available. This work was supported by the US DOE under Contract No. DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

10:40 AM

Step Structure of GaInAsSb Grown on Vicinal Substrates by OMVPE: *Christine A. Wang*[1]; Douglas C. Oakley[1]; [1]MIT Lincoln Laboratory, Electro-optical Mats. and Devices, 244 Wood St., Lexington, MA 02420-9108 USA

GaInAsSb alloys, which are important materials for mid-infrared optoelectronic devices, are predicted to be thermodynamically metastable over most of the alloy range. Earlier studies on the mechanism of phase separation for the III-V alloys suggest that it occurs at the surface during growth. Thus, a detailed understanding of the crystal growth process at the surface is beneficial for establishing experimental conditions that limit the extent of phase separation. In this paper, the step structure of metastable GaInAsSb epilayers with energy gaps corresponding to the 2 to 2.5 mm range is studied. GaInAsSb epilayers were grown by organometallic vapor phase epitaxy (OMVPE) with triethylgallium, trimethylindium, tertiarybutylarsine, and trimethylantimony as sources. The growth temperature was varied between 525 and 575°C. Layers were grown nominally lattice matched to (100) GaSb substrates with either a 2° toward (110) or 6° toward (111)B misorientation. Atomic force microscopy was used to study the surface topography. Multi-atomic step structures with a height of several monolayers are observed, which is indicative of a step-bunching growth mode as has been reported similarly for GaAs- and InP-based materials. The step structures are periodically arranged with features running perpendicular to the misorientation direction. In addition, a long range surface roughness is observed. Details of the dependence of the surface step structure on the OMVPE growth conditions, with alloy composition, temperature, substrate misorientation, and growth time as variables, are reported. In addition, the correlation between the step structure and the optical quality as measured by 4 K photoluminescence is presented.

11:00 AM

MOVPE Growth of Self-Assembled InSb Quantum Dots in a GaSb Matrix: *Nigel J. Mason*[1]; [1]University of Oxford, Dept. of Phys., Clarendon Laboratory, Parks Rd., Oxford OX1 3PU Great Britain

Self-assembled InSb quantum dots (QDs) embedded in a GaSb matrix were grown by metal organic vapour phase epitaxy at susceptor temperatures ranging from 460 to 500°C. Transmission electron microscopy (TEM) showed an (In,Ga)Sb wetting layer (WL) and the progressive stages of the growth of QDs. Strained QDs initially occurred followed by their co-existence with bigger, relaxed QDs and associated defects. Atomic force microscopy> (AFM) examinations that were performed on uncapped specimens revealed the co-existence of at least three different types of three-dimensional InSb islands and enabled accurate measurements of the islands' heights as well as estimations of their base widths. The TEM and AFM results were in reasonable agreement and showed that while a sub-species of the strained islands were of up to about 4 nm height and 30 x 30 nm2 base widths, the relaxed islands were typically of more than twice that height and had base widths of about 100 x 200 nm2. Typical number densities for the different is land types were in the lower 109 cm-2 range. Photoluminescence (PL) that was performed at 4.2 K showed typically WL emission at 0.770 eV and> QD emission at 0.735 eV. Magneto-PL was used to deduce the height and base widths of the luminescent QDs and the values obtained were in reasonable agreement with the TEM and AFM results that were obtained from the sub-species of strained InSb islands that possess an almost isotropic aspect ratio.

11:20 AM

Characterization of MOCVD GaInAsSb Epilayers for Mid-KR Photoelectronic Devices: *Ruiwu Peng*[1]; Wei Guangyu[1]; [1]Shanghai Institute of Metallurgy, Chinese Academy of Sciences, Shanghai 200050 China

GaInAsSb alloys are the most important materials for Mid-IR optoelectronic devices. In this paper the properties of unintentional and intentional MOCVD GaInAsSb (XIn= 0 ~ 0.3 and Ysb = 1 ~ 0.8) epilayers were characterized using PL, FTIR and DCXD together with the electrical measurements for fabricating good performance devices. The optoelectonic properties and crystallinity of MOCVD GaInAsSb epilayers were strongly influenced by GaSb substrate qualities. Using the best GaSb substrate wafers with specified parameters the good quality MOCVD GaInAsSb could be obtained. Their FWHM of PL and DCXD spectra are equal to about 14.5 mev and 200~300 arcsec respectively. For devices application we measured the variation of mobilities vs carrier concentrations of n- and p- doped MOCVD GaSb and GaInAsSb (Xin= 0.25 and Ysb= 0.8) epilayers with comparison of published data. The maximum doping levels in both Te and Zn doped GaInAsSb epilayers are reached to 1~2 x 1018 cm-3. We also determined the conduction types of GaInAsSb epilayers grown on GaSb substrates by thermoelectric probes using thermoelectric force or Seebeck voltage generated by a temperature gradient. It is found that the GaInAsSb epilayers became intrinsic, when Xin> 0.25. Thus, the longest wavelength of MOCVD GaInAsSb Mid-IR optpelectronic devices at room temperature may be limited to 2.5 *m. As a result, the 2.4 *m MOCVD GaInAsSb PIN photodetectors with detectivity of D > 1011Hz1/2w-1 at room temperature was fabricated.

Wednesday, Evening, May 26, 1999
Session IX
Posters

1. In-situ Post Annealing Treatment of Nitrogen Doped ZnSe Grown Using Photoassisted MOVPE: *Mashud U. Ahmed*[1]; Stuart J. C. Irvine[1]; [1]North East Wales Institute, Opto-Elect. Mats., Plas Coch, Mold Rd., Wrexham, Wales LL11 2AW UK

In this work, ZnSe:N on GaAs was grown using photo-assisted MOVPE at 380°C using the 458 nm wavelength from an Ar+ laser of intensity 90 mW/cm2 and DMZn, DESe and TMSiN3 precursors in a hydrogen carrier gas. PL spectra of these samples showed strong near band edge emission and DAP bands but with no deep level emission. SIMS analysis showed that high concentration of nitrogen up to 1 x 1019 atoms cm-3 were being incorporated, but the hydrogen concentration increased by the same amount and the material was resistive. To overcome this problem, various in - situ post growth techniques were carried out such as cooling under helium and nitrogen and also post - annealing in nitrogen at 500°C for 30 minutes. SIMS analysis showed that for samples post-annealed in nitrogen for 30 minutes, the hydrogen concentration decreased by an order of magnitude, but PL spectra of such samples showed strong and broad deep emission corresponding to self - activated defects, in addition to the near band edge emission, but the material remained resistive. The possible cause and solution to this problem will be discussed.

2. Dramatic Changes in Film Morphology Observed During Carbon Doping of Gallium Arsenide: *Michael J. Begarney*[1]; Lian Li[1]; Byung-Kwon Han[1]; Daniel C. Law[1]; Connie H. Li[1]; Robert F. Hicks[1]; [1]University of California, Los Angeles, Dept. of Chem. Eng., 5531 Boelter Hall, Los Angeles, CA 90095 USA

We have examined the effects of carbon doping on the surface morphology of gallium arsenide films grown by organometallic vapor phase epitaxy (OMVPE). Gallium arsenide was doped to $1x10^{20}$ cm^{-3} at 505-545°C using carbon tetrachloride, triisobutylgallium, tertiarybutylarsine, and a V/III ratio of fifty. These doping levels were also achieved by growing at 550-625°C using trimethylgallium, tertiarybutylarsine, and a V/III ratio below four. Carbon doping causes dramatic changes in the film morphology. For example, at 525°C using CCl4//esb and IV/III ratios between 0.08 to 0.3, step bunching is observed on the GaAs (001) surface. Alternatively, etch pits form at the same temperature when the IV/III ratio exceeds 0.4. These etch pits are 10 to 50 nm across, and result from preferential gallium chloride desorption at step edges. Step bunching is recorded during doping with trimethylgallium as well. The carbon doping mechanisms will be described at the workshop.

3. Influence of MOVPE Growth Conditions on the Structure of Interior Interfaces: *Georg C. Bernatz*[1]; Siegfried Nau[1]; Rasmus Rettig[1]; Wolfgang Stolz[1]; [1]Philipps-University, Mats. Sci. Center, Hans-Meerwein-Str., Marburg D-35032 Germany

The structural properties of interior interfaces are of key importance for the optical and transport properties as well as the device performance of semiconductor heterostructure layers. Here we describe a new method for the preparation of interior interfaces by highly selective, quasi-digital etching and subsequent investigation of the structural properties by atomic force microscopy (AFM). This method has successfully been applied to the (GaIn)As/InP, the (GaIn)P/GaAs and the AlAs/GaAs materials systems. In detail the influence of the MOVPE growth parameters (temperature, V/III-ratio, substrate off-orientation, switching sequence) on the structural properties of interior GaAs/AlAs interfaces (island structure and size, step density, microscopic roughness) is investigated. The structure of interior GaAs interfaces may vary drastically from that of an epitaxial GaAs surface after cooling-down. The correlation to the optical properties of GaAs quantum-well structures as obtained by photoluminescence excitation spectroscopy (PLE) will be presented and discussed.

4. Photoluminescence Studies of ZnSe and ZnTe Quantum Dots Grown by Metal-Organic Chemical Vapor Deposition: *Yuan-Huei Chang*[1]; Harris M. C. Liao[1]; M. H. Chieng[1]; C. C. Tsai[1]; Y. F. Chen[1]; [1]National Taiwan University, Dept. of Phys., 1 Roosevelt Rd., Sec. 4, Taipei, Taiwan 106 ROC

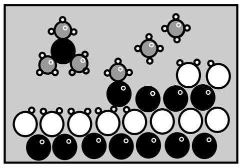
ZnSe and ZnTe quantum dots (QDs) were grown successfully by using growth-duration-control method with a metal-organic chemical vapor deposition system. The QDs were grown on rough surfaces and were embedded in ZnS, which acted as barrier layer for the QDs. It is found that when the growth duration of the QDs is small, the optical properties of the QDs are very good. Blue-shift as large as 300 and 250 meV were observed in the photoluminescence (PL) emission for ZnSe and ZnTe QDs, respectively. The emissions were found to persist up to room temperature. The blue-shift decreases as the growth duration increases, and for long growth duration no emission could be observed. From the temperature-dependent PL measurements, activation energy for thermal quenching of PL were obtained for QDs of different sizes. It is found that the activation energy decreases with increasing QD size, and is attributed to the break up of exciton in the QDs.

5. The Effect of InGaN Growth Rate on The Properties of InGaN Films Grown by Low Pressure Metalorganic Chemical Vapor Deposition: *Wen-Chung Chen*[1]; Chao-Nien Huang[1]; Chin-Yuan Chen[1]; Kwang-Kao Shih[1]; Kau-Feng Jan[1]; Su-Fen Hsieh[1]; Jeong-Yuh Chang[1]; [1]Industrial Technology Research Institute, Opto-Electronics and System Laboratories, Rm. 206, Bldg. 78, 195-8, Sec. 4, Chung Hsing Rd., Chutnung, Hsinchu 310 Taiwan ROC

The properties of InGaN films grown at different growth rates with the same reactor pressure and temperature of 200 mbar and 900 ÿ are studied. The total mole flow rates of group III are variable. The mole flow rate of NH3 and the ratio of TMIn to (TMIn and TMGa) are kept constant to be 3 l / min and 6%. Within these InGaN films the In composition increases from 5 to 20% with increasing growth rate from 20 to 120 Å / min. Besides, the photoluminescence intensity evidently increases with increasing growth rate. Since the flow rate of TMGa directly affects the growth rate of InGaN films, the growth mechanism is suggested to be prevailed by evaporation than by deposition of element Indium at such growth temperature in this study. And a promised performance of quantum well LED with 20 wells could be carried out with a high growth rate of InGaN films.

6. Next Generation Adduct Purification Techniques for Low Oxygen Content Alkyls: *Kathleen M. Coward*[1]; Anthony C. Jones[1]; Martyn E. Pemble[1]; Lesley M. Smith[2]; [1]University of Salford, Dept. of Chem. and App. Chem., Salford, England M5 4WT UK; [2]Epichem, Ltd., Tech. Products, Power Rd., Bromborough, Wirral, Merseyside L62 3QF UK

The rapid expansion in the MOCVD of optical III-V devices makes it important to lower the level of oxygen impurities in Group III metalorganic precursors. Although conventional adduct purification techniques are highly effective at removing trace metals from the precursor, they are less effective at removing oxygen contaminants. New synthesis and purification techniques are therefore required to address this problem. The oxygen levels in the metalorganic precursor can be significantly reduced by replacing Et2O with NEt3 during synthesis. This leads to adducts of the type R3M(NEt3) (R = Me, Et; M = Ga, In) which have rather low vapour pressures for general MOVPE applications. However, the addition of cyclic aza-crown ligands, containing 4N and 6N sites, displaces the NEt3 to give novel adducts, (R3M)4L and (R3M)6L, from which the base-free metalorganic can be obtained by mild thermal dissociation. In this presentation the synthesis, characterisation and thermal dissociation of these adducts is described.



7. High C-Doping of MOVPE Grown Thin $Al_xGa_{1-x}As$ Layers for AlGaAs/GaAs Interband Tunneling Devices: *Frank Dimroth*[1]; Andreas W. Bett[1]; Peter Lanyi[1]; Ute Schubert[1]; [1]Fraunhofer Institute for Solar Energy Systems ISE, SWT, Oltmannsstr. 5, Freiburg, Baden-Wuerttemberg 79100 Germany

We investigated the growth of $Al_xGa_{1-x}As$-(C)/GaAs-(Si) interband tunnel junctions for a series connection of GaInP/GaAs tandem concentrator solar cells. This work was performed on an AIX2600-G3 multiwafer MOVPE reactor with a capacity of 5 times 4" substrates. We investigated the growth of C-doped $Al_xGa_{1-x}As$ layers with an active bulk carrier concentration > 10^{20} cm^{-3}. The layers were intentionally doped using TMAl and TMGa together with small V/III ratios and low growth temperatures. SIMS and Hall measurements were performed to investigate the influence of the Al-content on the oxygen incorporation and C donator activity. Unfortunately, a low growth temperature of about 530°C has to be used to achieve a high C-doping concentration in combination with a good lateral homogeneity and surface morphology. On the other hand, higher temperatures are needed for sufficient Si incorporation into the n-doped layer of the tunnel junction. Therefore, delta-doped pipi-$Al_xGa_{1-x}As$ structures grown at temperatures exceeding 600°C are under investigation. Current-voltage characteristics of bulk- and delta-doped tunneling junctions will be presented.

8. The Use of Solution TrimethylindiumÔ for the Growth of InAlP/InGaP Double Heterostructures and Superlattices: Yuichi Sasajima[1]; Richard D. Heller[1]; Russell D. Dupuis[1]; Ravi Kanjolia[2]; Barry Leese[3]; Lesley Smith[3]; [1]The University of Texas at Austin, Microelectronics Research Center, PRC/MER 1.606D,R9900, Austin, TX 78712-1100 USA; [2]Epichem, Inc., 26 Ward Hill Ave., Haverhill, MA 01835-0730 USA; [3]Epichem, Ltd., Power Rd., Bromborough, Wirral L62 3QF UK

We have studied the use of solution trimethylindiumÔ (STMIn) for the growth of InAlGaP heterostructures and superlattices on GaAs substrates by low-pressure metalorganic chemical vapor deposition. We have examined the lattice matching control and the purity of InAlP and InGaP layers grown using various trimethylindium (TMIn) sources. We have grown InAlP/InGaP double heterostructures (DHs) and InAlGaP/InGaP superlattices (SLs) using different In sources including STMIn and solid TMIn, and different phosphine cylinders. The optical properties of these films have been measured by 300K and 4.2K photoluminescence (PL), and impurity concentrations have been analyzed by secondary ion mass spectroscopy. We have obtained PL spectra with larger intensities and narrower full width at half maximum values for DH and SL structures grown using solution TMIn. In the SIMS profiles, we observe lower oxygen incorporation in both InAlP and InGaP layers grown using STMIn compared with solid TMIn from similar batches of TMIn. Furthermore, the oxygen incorporation into the layers was dependent on purity of phosphine as well. These results indicate growth with solution TMInÔ and high-purity phosphine can improve the quality of InAlP and InGaP dramatically.

9. OMVPE of GaN Using Tailored Single Molecule Precursors: *Roland A. Fischer*[1]; Wolfram Rogge[1]; Thorsten Johann[1]; [1]Ruhr-University Bochum, Inorganic Chemistry, Universitaetsstrasse 150, Bochum, NRW D-44780 Germany

Intermolecularly adduct stabilized organo group-13 azides of the general formula (N3)aER3-a (E = Al, Ga, In; a = 1, 2; R = [(CH2)nNR'2] and [N(R'')(CH2)mNR'2]) are used for the epitaxial growth of GaN and InN on GaAs(001), Si(111) and Al2O3(0001) at substrate temperatures between 300 and 1100°C in the absence of ammonia or other additional N-sources. Monitoring the gas phase composition of the boundary layer gave evidence for nitrogen rich fragments of the type HENx and ENx (x = 1-6). The temperature dependent concentration of this fragments correlate with the growth rates of 1- 10 um/h. The properties of the obtained nitride films characterized by PL, RBS, ERDA, AFM, XPS and XRD will be discussed. In a typical experiment, BIZIGA (bisazido-dimethylaminopropyl-gallium) was employed to grow GaN at 800°C in a cold wall reactor [FMWH(0002): 0.72°; PL(\@298K): 3.4 eV].

10. Comparison of Hydrazine and Tertiarybutylamine Nitrogen Sources as Alternatives to Dimethylhydrazine for OMVPE Growth of GaInNAs: *Daniel J. Friedman*[1]; John F. Geisz[1]; *Sarah R. Kurtz*[1]; [1]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

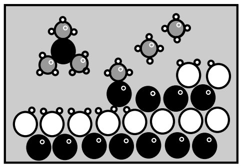
Dimethylhydrazine (DMHy) has been shown to be an effective nitrogen source for the growth of the alloy $Ga_xIn_{1-x}N_yAs_{1-y}$ (x,y << 1). However, high DMHy flow rates are required, and high p-type background doping concentration and low diffusion lengths are typically observed in the grown material. It is therefore of interest to evaluate alternative nitrogen sources. Here, we evaluate two such sources: hydrazine and tertiarybutylamine. Hydrazine is of particular interest because it contains no carbon, suggesting that it might yield lower p-type background doping than DMHy does. With tertiarybutylamine, no nitrogen incorporation was observed, even with nitrogen/III ratios as high as 2000, and so does not appear promising. With hydrazine, by contrast, significant nitrogen incorporation was observed, even at much lower nitrogen/III ratios than would be required using DMHy. However, the p-type background doping appears no lower than with DMHy. Possible origins for this background are discussed.

11. A Comparison of TMG with TEG for the Growth of InGaAs: *Richard William Glew*[1]; Karen A. Grim-Bogdan[1]; Nikolaos Tzafaras[1]; Shohei Nakahara[1]; [1]Lucent Technologies, Optoelectronics, 9999 Hamilton Blvd., Breinigsville, PA 18031 USA

We report on the growth of InxGa1-xAs on InP substrates in a multi-wafer low pressure MOCVD reactor over a wide range of growth conditions. We have compared TMG with TEG while using TMI and Arsine. For the first time, we have observed that the lattice mismatch of InxGa1-xAs with respect to InP is strongly influenced by the Arsine concentration when grown with TEG and TMI. The lattice mismatch of InxGa1-xAs was positive for a low Arsine flow and negative for a high Arsine flow, for the same TMI and TEG flows. In contrast, for TMG and TMI, the InxGa1-xAs lattice mismatch was independent of Arsine concentration. We shall propose a new model for the interaction between the group III and group V species at the growing surface, which will explain why the growth rate of InxGa1-xAs is higher for TMG than for TEG with the same TMI and Arsine flow. We have utilized this effect for the growth of strain compensated InxGa1-xAs / InyGa1-yAs superlattices by modulating the Arsine flow into the reactor chamber while keeping the TEG and TMI constant. Structures, with up to 100 periods of 100Å of +1% InxGa1-xAs and 200Å of -0.5% InyGa1-yAs, were grown with excellent characteristics. Growth without relaxation was confirmed by cross-sectional TEM analysis.

12. Trace Contaminants in Metalorganic Source Chemicals: Lawrence James Guilbault[1]; Kei May Lau[2]; Yudong Qi[2]; [1]Morton International, Inc., Morton Metalorganics, 60 Willow St., North Andover, MA 01845 USA; [2]University of Massachusetts, Dept. of Elect. & Comp. Eng., Marcus Hall, Amherst, MA 01003 USA

Low level organic and inorganic contaminants in metalorganic source chemicals can adversely affect the performance of compound semiconductor film in electronic and optoelectronic devices. Since the Group II or Group III metal is initially derived from mining operations, it is invariably contaminated with other elements present in the earth's crust. Organic and oxygenated organic contamination can be introduced during manufacture of the metalorganic due to impurities in alkylating agents, reaction byproducts or residual solvents from the chemical synthesis. Identification and quantification of ppm and sub-ppm levels of impurities in pyrophoric metalorganics, and correlation with the film performance presents a difficult technical challenge. Whether the existance and at what level of a specific impurity is relevant or detrimental to the electrical and optical properties of the grown layers is the key question. In this work, we attempt to provide some answers. Organic impurity analysis by FTNMR, GC and GCMS has aided in developing improved manufacturing processes to reduce organic contami-



nants. Speciation and quantification of inorganic impurities by ICP, ICP-MS, SSMS and Quadrapole MS has enabled correlation with electrical characteristics (low temperature mobility and carrier concentration) and SIMS analysis of grown films. These basic analyses will aid users of metalorganic source chemicals to determine the suitability of the chemical for their specific device applications.

13. Order Parameter Determination Using High Resolution X-ray Diffraction: Ron R. Hess[1]; Caroline D. Moore[1]; R. Tage Nielsen[1]; *Mark S. Goorsky*[1]; [1]University of California, Los Angeles, Dept. of Mats. Sci. and Eng., 6532 Boelter Hall, Los Angeles, CA 90095-1595 USA

We have developed high resolution x-ray diffraction techniques to determine the order parameter in nominally lattice-matched In$_x$Ga$_{1-x}$P epitaxial layers deposited on GaAs by metal organic vapor phase epitaxy. Earlier work on ordering in semiconductor materials relates the width of the x-ray diffraction peak to the size of the ordered domain, but does not predict the order parameter. In this study, a matrix of samples with different amounts of ordering was obtained by varying the substrate miscut and epilayer growth temperature. A combination of ½(115) and (224) reflections in double axis was employed to compare diffracted intensities of standard and “ordered” reflections with approximately the same beam footprint. Only one strong variant was observed in each case, consistent with the presence of a miscut. The composition was also determined by x-ray diffraction and combined with luminescence measurements to provide an independent measurement of the degree of ordering. The values for the ordered parameter obtained were in agreement with those from diffraction. Dynamical simulations of CuPt-ordered InGaP were also used to refine the order parameter determination. Initial triple axis diffraction reciprocal space maps from the "ordered" reflections also indicated that the peak width is not always related to a domain size but rather to misorientation among the ordered domains.

14. Pressure Dependent Bandgap Energies and Masses in 1eV InGaAsN Lattice Matched to GaAs: *Eric D. Jones*[1]; Norman A. Modine[1]; Andy A. Allerman[1]; S. R. Kurtz[1]; Alan F. Wright[1]; Stan T. Tozer[2]; Xing Wei[2]; [1]Sandia National Laboratories, Dept. 1113, MS-0601, P.O. Box 5800, Albuquerque, NM 87185-0601 USA; [2]Florida State University, National High Magnetic Field Lab., 1800 E. Paul Dirac Dr., Tallhassee, FL 32306-4005 USA

We have studied the pressure dependence of the bandgap energy and conduction-band mass in a 1eV InGaAsN alloy (lattice matched to GaAs). All measurements were made at 4.2K. The nominal In and N concentrations were respectively 7 and 2%. The bandgap energy at ambient pressure is about 1100 meV. Band masses were determined from the exciton diamagnetic shifts between 0 and 30 tesla. The pressures were generated using a diamond anvil cell. At the maximum applied pressure of 110 kbar, the bandgap energy shift is nearly 400 mev. The results of a first principles LDA band structure for this alloy system will be presented. The agreement between the measured and theoretical pressure change to the bandgap energy is excellent. The ambient pressure masses are found to be about 2 to 3 times heavier than GaAs. The pressure dependence of the mass will also be presented and a comparison with the LDA predictions will be made.

15. OMVPE Growth and Properties of High Quality Piezoelectric InGaAs/GaAs Quantum Well Structures on <111> Oriented GaAs Substrates: *Jongseok Kim*[1]; Alfredo Sanz-Hervás[1]; Soohaeng Cho[1]; Constantino Villar[2]; Joel Díaz[2]; B. W. Kim[3]; Arnoldo Majerfeld[1]; [1]University of Colorado, Dept. of Elect. and Comp. Eng., CB425, Boulder, CO 80309 USA; [2]E.T.S.I. Telecomunicación, UPM, Ciudad Universitaria, Madrid 28040 Spain; [3]Electronics and Telecommunications Research Institute, P.O. Box 106, Yusong, Taejon 305-600 Korea

Epitaxial growth of strained InGaAs/GaAs Quantum Well (QW) structures on substrates oriented in the <111> crystallographic directions opens a number of possibilities for novel optoelectronic devices because of the existence of a large piezoelectric field in the QW region. Almost all the studies to date on this type of structures were performed on MBE grown materials. We report for the first time the growth of InGaAs/GaAs QW structures on (111) GaAs substrates by atmospheric pressure OMVPE. The growth conditions and their effects on the structural and optical properties will be presented. The QW structures were extensively analyzed by means of high resolution X-ray diffractometry, photoluminescence and photoreflectance measurements in combination with theoretical computations which included the potential modifications in the well and barrier regions resulting from the piezoelectric field. Excellent crystal quality, interface abruptness and roughness have been proven. For a 41Å wide QW, interfaces with ±1 monolayer roughness were obtained.

16. BaTiO$_3$ Film Growth by MOCVD Using BaDPM2-Tetraen2 as Ba Prescuror: *M. K. Lee*[1]; H. C. Lee[1]; R. H. Horng[2]; D. S. Wuu[2]; J. Gong[3]; [1]National Sun Yat-sen University, Dept. of Elect. Eng., Taiwan 80424 ROC; [2]Da-Yeh University, Dept. of Elect. Eng., Changhua, Taiwan 515 ROC; [3]National Tsing Hua University, Dept. of Elect. Eng., Hsingchu, Taiwan 30043 ROC

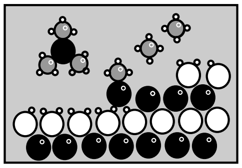
The ferroelectric BaTiO3 thin films have been attracted for the fabrication of high density dynamic random access memories in very large scale integrated circuits. The Ba(DPM)2-tetraen2 was used as Ba precursor that has much higher vapor pressure than typical Ba sources such as Ba(DPM)2 in this study. Mirror-like surface of BaTiO3 thin films were deposited by MOCVD on p-Si(100) and RuTi/Si using the precursors of Ba(DPM)2-tetraen2, Ti(i-OC3H7)4 and N2O in the temperature range of 500~800ÿ. The growth rate of BaTiO3 was about 18~24 Å /min under current preparation conditions. The structure is polycrystalline by X-ray examination and the main peak is at 2q=29° by Cu Ka. The cross section observed by SEM has column structure. The column size increases with the increase of Ba. The Ba content seems to be associated with the Ti content by SIMS analyses. Ellipsometric measurement shows that the refraction index of BaTiO3 films can reach 2.4. The leakage current was about 344nA/cm2 under 106 V/cm at thickness of 450Å. The high leakage current could come from the column structure and oxygen insufficiency. The dielectric constant determined by the capacitance-voltage measurement was 17.

17. Growth of Very High Intensive Photo- and Electro-Luminescence of Bulk In0.2Ga0.8N and In0.2Ga0.8N/GaN QW LED Structures: *Gang Li*[1]; Soo Jin Chua[1]; Wen Wang[1]; Peng Li[2]; [1]Institute of Materials Research and Engineering, Opto-electronics and Photonics, 10 Kent Ridge Crescent (NUS) 119260 Singapore; [2]National University of Singapore, Center for Opto-electronics, Dept. of Elect. Eng., 10 Kent Ridge Crescent 119260 Singapore

A parametric study has been carried out to optimize growth conditions for very high intensive photoluminescence of bulk InxGa1-xN on GaN. The effect of growth parameters, including growth temperature, V/III molar ratio, TMIn and TMGa molar ratio and InxGa1-xN growth rate on room temperature photoluminescence intensity of InxGa1-xN is reported. We found that similar to previous reports, the In molar fraction is very sensitive to growth temperature, while the other parameters only have little effect on In molar fraction but can strongly affect optical properties of In0.2Ga0.8N grown at one particular temperature. Further characterization results obtained using PL, XRD, RBS, and TEM show that the phase separation and defects related recombination are both or either possibly responsible for very high intensive photoluminescence of In0.2Ga0.8N. Those experimental results have been applied to fabricate In0.2Ga0.8N/GaN QW LED structures. A very high intensive blue electro-luminescence was obtained and their possible links with optical properties of bulk In0.2Ga0.8N on GaN are discussed.

18. Characterization of GaAs Organometallic Vapor Phase Epitaxy by Scanning Tunneling Microscopy: *Lian Li*[1]; Robert F. Hicks[1]; Byung-Kwon Han[1]; Daniel Law[1]; Connie Li[1]; [1]University of California, Los Angeles, Dept. of Chem. Eng., 405 Hilgard Ave., Los Angeles, CA 90095 USA

A scanning tunneling microscope (STM), as well as other surface science instruments, has been interfaced to an organometallic vapor phase epitaxy



(OMVPE) reactor. This has allowed us to conduct a detailed study of the nucleation and growth of gallium arsenide films as a function of the growth conditions. The root-mean-square roughness and the height-height correlation function have been measured over a range of temperatures, V/III ratios and growth rates. The height-height correlation function follows a power law dependence on distance up to a critical distance, l, after which it saturates. The value of l is larger than 20 nm, and increases with increasing substrate temperature and decreasing growth rate. A rate law also has been developed to describe the dependence of the surface roughness on the growth parameters. The significance of the roughness and height functions, and their use in assessing the growth process, will be described at the meeting.

19. Epitaxial Growth of CdZnTe-CdSeTe Films by Remote Plasma Enhanced Metal Organic Chemical Vapor Deposition: *Daiji Noda*[1]; Toru Aoki[1]; Yoichiro Nakanishi[2]; Yoshinori Hatanaka[2]; [1]Shizuoka University, Graduate School of Elect. Sci. and Tech., 3-5-1, Johoku, Hamamatsu, Shizuoka 432-8011 Japan; [2]Shizuoka University, Research Institute of Electronics, Graduate School of Elect Sci. and Tech., 3-5-1, Johoku, Hamamatsu, Shizuoka 432-8011 Japan

Metal organic chemical vapor deposition (MOCVD) technique has intensively been investigated in the field of epitaxial films growth. In this study, we have carried out the epitaxial growth of CdZnTe-CdSeTe films using a remote plasma enhanced (RPE) MOCVD method. Hydrogen radicals generated by inductively coupled rf remote plasma were introduced into the reaction region. Therefore, these film growth processes were carried out at the low substrate temperature of 200°C. In this deposition method, $\mathrm{Cd_{1-X}Zn_XTe}$, $\mathrm{CdSe_XTe_{1-X}}$ films with the composition ratio x in the range of 0 to 1 have been obtained while varying the ratio of group II, and VI source, respectively. The role of hydrogen radicals were considered as to decompose the metal organic source materials and to help the surface reaction for the film formation. This results suggest that the RPE-MOCVD method can be one of the promising method in preparing CdZnTe-CdSeTe epitaxial films.

20. Investigation of Trace Impurities in Hydride Gases by GC/AED: *Mark W. Raynor*[1]; Virginia H. Houlding[1]; Terry L. Ramus[2]; Scott J. Hein[2]; Michael J. Domeniconi[3]; Ralph W. Kirk[3]; [1]Matheson Gas Products, Advanced Technology Center, 1861 Lefthand Circle, Longmont, CO 80501 USA; [2]Diablo Analytical, Inc., 1110 Burnett Ave., Suite C, P.O. Box 5889, Concord, CA 94520 USA; [3]Matheson Electronic Products Group, 625 Wool Creek Drive, San Jose, CA 95112 USA

Many micro-electronic devices can only be manufactured using ultra-high purity specialty gases. For III/V semiconductors, epitaxial thin films are grown by MOCVD using ultra-pure ammonia, phosphine and arsine, to supply the group V elements. These films are then fabricated into lasers and LEDs. Unfortunately, trace gas impurities containing Si, S, Ge and C can incorporate into the films and degrade the performance of the device. As a result it is very important to develop state-of-the-art analytical techniques for qualitative and quantitative measurement of these impurities at the ppt-ppb level. Gas chromatography combined with atomic emission detection (GC/AED) is capable of simultaneous multi-element selectivity, quantitative response and excellent sensitivity. However, for successful results, the instrument must be modified to handle and sample toxic gases, column separation and detector parameters must be optimized and the instrument must be calibrated. In this paper, we present and discuss GC/AED techniques for this important application.

21. Effects of Substrate Misorientation On Patterned Substrate Organo Metallic Vapor Phase Epitaxy of GaAs: *Walter Reichert*[1]; Richard M. Cohen[1]; [1]University of Utah, Dept. of Mats. Sci. and Eng., 160 S Central Campus Dr., Rm. 304 EMRO, Salt Lake City, UT 84112 USA

GaAs growth on patterned <100> on-axis and off-axis GaAs substrates was studied. Time resolved (5 minutes to 4 hours growth time, growth rate=1.5 µm / hour) OMVPE growth of GaAs was performed on square and cross-shaped GaAs mesas (50nm to 1.5µm high). The <100> off-axis substrates were 2° misoriented towards <110> or 3° misoriented towards <110>, <0-11>, <0-1-1>, or <01-1>. Before and after growth the mesas were characterized by optical microscopy, AFM, and SEM. It was found that not only the growth conditions (temperature, group V partial pressure) determine the lateral/vertical growth rate ratio on GaAs mesas but the direction of the misorientation of <100> substrates from <100> and the mesa orientation on the substrate have a substantial influence on the developing growth profile. Depending on the substrate misorientation lateral growth and ridge formation at the mesa edges can be enhanced or suppressed in a given crystallographic direction.

22. Properties of InAlGaP Alloys and Devices Grown with Low-Oxygen Trimethylindium: *Y. Sasajima*[1]; R. D. Heller[1]; R. D. Dupuis[1]; R. H. Pearce[2]; [1]The University of Texas at Austin, Microelectronics Research Center, Austin, TX 78712-1100 USA; [2]AZKO Nobel Inc., Deer Park, TX 77536 USA

Oxygen is a known contaminant in trimethylindium (TMIn) which can play a strong role in the performance of light-emitting devices, e.g., lasers and light-emitting diodes. The concentration of certain oxygen-containing impurities in organometallic sources can be directly measured by NMR spectroscopy to estimate the performance of various organometallic sources for device applications that are sensitive to oxygen. We have studied the use of low-oxygen trimethylindium (TMIn) for the growth of InAlGaP heterostructures of GaAs substrates by low-pressure metalorganic chemical vapor deposition. We have grown InAlGaP hetrostructures (DHs) and InAlGaP/InGaP superlattices (SLs) using different In sources and different phosphine cylinders. The optical properties of these films have been measured by 300K and 4.2K photoluminescence (PL), and oxygen impurity concentrations have been analyzed by secondary ion mass spectroscopy (SIMS). We have observed a strong correlation of the properties of these films with the NMR data taken on the organometallic source. The PL intensities are higher and the full width at half maximum values are narrower for structures grown using low-oxygen TMIn. As expected, the SIMS profiles show lower oxygen incorporation in both InAlP and InGaP layers grown using low-oxygen TMIn compared with TMIn from batches having concentrations of oxygen-containing impurities as determined by NMR. We will present data on the quality of materials and the performance of devices fabricated with the low-oxygen sources.

23. Properties of Solution TMI as an OMVPE Source: *Lesley Smith*[1]; Megan Ravetz[1]; Simon Rushworth[1]; A. B. Leese[1]; Ravi Kanjolia[2]; [1]Epichem, Ltd., Research Dept., Power Rd., Bromborough, Wirrall L62 3QF UK; [2]Epichem, Inc., 26 Ward Hill Ave., P.O. Box 8230, Haverhill, MA 01835-0730 USA

Solid trimethylindium (TMI) is the precursor of choice for the vast majority of MOVPE applications. However, consistent pick up has been proved problematic under normal operating conditions. Epichem’s solutions to this problem have included "solution TMI" (TMI suspended in a high boiling point amine adducted to TMI) and reverse flow dual bubblers of solid TMI. This presentation will detail work on “solution TMI” using an ultrasonic analyser, Epison III to monitor the concentration of TMI in the gas stream. The results presented show the high stability of TMI concentration in the vapour phase, and the physical properties of the “solution TMI” in the bubbler. Side-by-side trials comparing “solution TMI” with solid TMI have shown that the background carrier concentration and oxygen levels in AlInAs are reduced by an order of magnitude when the former is used. Consequently "solution TMI" has been identified as the best precursor for low oxygen applications.

24. MOCVD of MgO Utilizing a Novel Mg bis(b-ketoiminate): *Jason S. Matthews*[1]; Oliver Just[1]; Bettie Obi-Johnson[1]; William S. Rees[1]; [1]Georgia Institute of Technology, Molecular Design Institute, School of Chemistry and Biochemistry, Atlanta, GA 30332-0400 USA

Chemical vapor deposition utilizing a new, highly volatile magnesium bis(b-ketoiminate) was carried out in a hot-walled CVD reactor under an inert atmosphere of argon. The precursor temperature was maintained between 225-232°C with an argon flow rate of 20-30 sccm. The silicon substrate was held at a temperature of 450°C. Analysis of the deposited films by XPS shows that the chemical composition of the film corresponds to that of magnesium oxide. The SEM micrographs show a uniform particle size of approximately 150 nm. The homoleptic bis(b-ketoiminate) compound was prepared by reacting dibutylmagnesium with 2 equivalents of 5-N-(N,N-dimethylaminopropyl)-2,2,7-trimethyl-3-octanone in THF. Its molecular structure, determined by the single crystal X-ray diffraction technique, exhibits a six-coordinate magnesium atom surrounded by four nitrogen and two oxygen atoms in an octohedral environment.

25. High-Responsivity GaInAs/InP Quantum Well Infrared Photodetectors Grown by Low-Pressure Metalorganic Chemical Vapor Deposition: *M. Erdtmann*[1]; M. Rutz[1]; S. Vaish[1]; M. Razeghi[1]; M. Massie[2]; [1]Northwestern University, Center for Quantum Devices, 2145 Sheridan Rd., Evanston, IL 60208 USA; [2]Nova Research, Inc., 437 Second St., Suite B, Solvang, CA 93463 USA

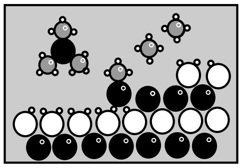
Quantum well infrared photodetectors (QWIPs) are sensitive to the mid- and far-infrared regions of the spectrum while containing only wide-bandgap alloys such as AlGaAs or GaInAs. They accomplish this by making use of intersubb and absorption with a multi-quantum well stack, which can consist of over 100 very thin layers. Since their realization over a decade ago, the growth of such structures has been dominated by molecular beam epitaxy. Significantly less work has been performed with devices grown by metalorganic chemical vapor deposition (MOCVD), especially those comprised of material systems other than GaAs/AlGaAs. We have grown high-quality GaInAs/InP QWIP structures using low-pressure MOCVD and fabricated them into detectors. The QWIP structure consists of 20 quantum wells of nominally 60 Å thick n-GaInAs (n = 2 x 1017 cm-3) surrounded by 500 Å thick undoped InP barriers. On each side of the well region are top and bottom n-GaInAs contact layers (n = 5 x 1017 cm-3), having thicknesses of 0.50 mðm and 0.75 mðm, respectively. The samples were grown on semi-insulating InP substrates. The x-ray diffraction spectrum of a QWIP structure is shown in Fig. 1 along with its simulated spectrum. The spacing of the peaks and the modulation of the peak intensities reveals a barrier thickness of 499 Å and a well thickness of 63 Å. The room temperature photoluminescence spectrum of the same structure is graphed in Fig. 2. The FWHM of the peak is only 41 meV. Both of these attest to the crystalline quality of the structure. The QWIPs were fabricated by defining 400 x 400 mðm mesas with wet etching and applying Ti/Pt/Au metal contacts to the top and bottom contact layers. The detectors were then measured under normal incidence conditions without the use of any special gratings and exhibited extremely strong responsivity and high specific detectivity. At an operating temperature of 77 K, the responsivity is 14.6 A/W at a bias of +5 V, which when taken with respect to the applied electric field is better than that of other reported QWIPs near this wavelength. The plot of responsivity versus bias is pictured in Fig. 4. The maximum detectivity is 1.9 x 1010 cmHz1/2W-1. It is possible to have high-performance QWIPs that (a) are grown by MOCVD and (b) do not require any kind of grating or optical coupler.

26. OMVPE Growth and Characteristics of Almost 1.2 um GaInNAs-GaAs Three-Quantum-Well Laser Diodes: *Nein-Yi Li*[1]; Chris P. Hains[4]; Kai Yang[4]; Pei-wen Li[2]; M. Moorthy[3]; X. Weng[3]; Rachel S. Goldman[3]; Julian Cheng[4]; [1]Emcore Corporation, EmcoreWest, 10420 Research Rd., Albuquerque, NM 87123 USA; [2]Yi-So University, Dept. of Electr., Ta-Su, Taiwan; [3]University of Michigan, 2300 Hayword St., Ann Arbor, MI 48109-2136 USA; [4]University of New Mexico, CHTM, 1313 Goddard Ave. SE, Albuquerque, NM 87122 USA

We report, for the first time, the OMVPE growth and optical characteristics of 1.17-1.20 um GaInNAs/GaAs laser diodes with three Ga0.7In0.3N0.003As0.997/GaAs quantum wells. Photoluminescence, secondary ion mass spectroscopy, atomic force microscopy, transmission electron microscopy, and light-current characteristics were analyzed to evaluate performance of Ga0.7In0.3N0.003As0.997/GaAs laser diodes. Edge emitting laser diodes with three Ga0.7In0.3N0.003As0.997(7 nm)/GaAs(10 nm) QWs were grown by OMVPE using dimethylhydrazine as the N precursor. Strong room-temperature PL at the 1.17-1.19 um regime with a full width at half maximum of 33 meV has been routinely achieved. For broad-area laser diodes with the stripe width of 60 um and the cavity length of 1000 um, a threshold current density of 1.0 KA/cm2 has been successfully demonstrated, and, to our best knowledge, it is the lowest value among the OMVPE-grown 1.17-1.20 um Ga1-xInxNyAs1-y laser diodes reported to date (Jth>3.4 KA/cm2) with comparable device structures. This paper will briefly discuss the GaInNAs material properties, tellurium memory effects on optical properties, and room-temperature operation characteristics of Ga0.7In0.3N0.003As0.997/GaAs laser diodes by using novel in-situ HCl etching and OMVPE regrowth techniques. The authors prefer to present an oral paper.

27. Lateral Epitaxial Overgrowth of Quasi Dislocation Free GaN on Sapphire and Silicon Substrates: *Patrick Kung*[1]; Manijeh Razeghi[1]; [1]Northwestern University, Center for Quantum Devices, Dept. of Electr. & Comp. Eng., 2145 Sheridan Rd., Evanston, IL 60208 USA

Lateral epitaxial overgrowth (LEO) has become the most promising growth method to achieve quasi dislocation free GaN thin films. This technique is also advantageous because it can be potentially applied on any type of substrate, including basal plane sapphire and silicon substrates. In this paper, we present the LEO growth and characterization of GaN films by low pressure metalorganic chemical vapor deposition. The first step consisted of growing a high quality III-N template layer on (00.1) sapphire and especially (111) Si substrates which served as the “seed” material for the subsequent LEO crystal. Highly oriented crystalline GaN was achieved directly on (111) Si, with x-ray diffraction linewidths narrower than 11 arcmins. This was followed by the deposition of a SiO2 dielectric film and its patterning into a specific stripe-like geometry. Various stripe widths, spacings and orientations with respect to the underlying GaN template layer were investigated. The LEO growth of GaN was then conducted on the thus patterned structure. The LEO films were extensively characterized through x-ray diffraction, scanning and transmission electron microscopy (SEM, TEM), atomic force microscopy (AFM), photoluminescence and cathodoluminescence. Similarly high quality LEO grown GaN was achieved on sapphire and Si substrates. Figure 1 shows the cross-section SEM micrograph of a fully coalesced LEO grown GaN on sapphire and Si substrates. The x-ray diffraction spectra generally exhibited three peaks for the GaN, which suggests that the LEO grown GaN was strained differently than the template layer. The photoluminescence from these wafers strong bandedge excitonic emission at 300 K and 77 K with negligible deep level emissions. Atomic force microscopy showed that the GaN laterally grown over the dielectric mask was smoother than the GaN grown in the mask opening windows. The former was also free of threading dislocations as evidenced by the absence of dots in the AFM images, whereas the latter exhibited such dots (Figure 2). Cross-sectional TEM micrographs showed that the laterally overgrown GaN was quasi dislocation free. The GaN grown in the mask opening windows still exhibited a number of threading dislocations. In an effort to eliminate these remaining extended defects, “double LEO” was conducted. This consisted of applying the LEO concept on an already coalesced GaN LEO film, but shifting the stripe pattern so that the dielectric mask covers the previously open areas and thus stops the propagation of threading dislocations when regrowing a second time. The cross sectional SEM micrograph of the resulting structure is shown in Figure 3. Additional material characterization results and preliminary device fabricated using LEO GaN will be presented. Figure 1. Fully coalesced single LEO grown GaN on (a)



sapphire and (b) Si substrates. Figure 2. Atomic force micrographs of an LEO grown GaN on sapphire, showing the regions above the dielectric mask and over the mask opening. Figure 3. Fully coalesced double LEO grown GaN on sapphire substrates.

28. 1,1-Dimethylhydrazine as a High Purity Nitrogen Source for MOVPE-Water Reduction and Quantification using NMR, GC-AED and Cryogenic-MS Analytical Techniques: *R. Odedra*[1]; L. M. Smith[1]; M. S. Ravetz[1]; S. A. Rushworth[1]; J. Clegg[1]; R. Kanjolia[2]; S. J. C. Irvine[2]; M. Ahmed[2]; E. D. Bourret-Courchesne[3]; N. Y. Li[4]; J. Cheng[4]; [1]Epichem Ltd., Power Rd., Bromborough, Wirral L62 3QF UK; [2]Optoelectronic Materials Research Laboratory, NEWI, Plas Coch, Mold Rd., Wrexham L111 2AW UK; [3]Lawrence Berkeley National Laboratory, MS 2-200, 1 Cyclotron Rd., Berkeley, CA 94720 USA; [4]University of New Mexico, Center for High Technology, 1313 Godard Ave. SE, Albuquerque, NM 87106 USA

Recent studies have shown that 1,1-dimethylhydrazine is a clean and efficient source of nitrogen for the growth of group III nitrides [1,2]. It has also been used to incorporate up to 4% nitrogen in GaInAs layers for solar cells with photoresponse down to 1 eV[3] and LED's with light emissions between 1.2 to 1.45 mm for telecommunications [4]. Here for the first time we report a correlation between ^{1}H NMR spectroscopy, GC-AED and cryogenic-MS for the quantity of water present in 1,1-dimethylhydrazine. We also report the highest purity material obtained to date. The high quality of 1,1-dimethylhydrazine using method 7 is confirmed by the growth test results. MOCVD-grown InGaAsN lasers with emission at 1.18 mm have the lowest threshold current density among either MBE or MOCVD-grown InGaAsN laser diodes reported to date. References [1] A. Ougazzaden et al, Appl. Phys. Lett., 70 (1997) 2861. [2] H. Tachibana, J. F. T. Geist, S. R. Kurtz and J. M. Olson, J. Cryst. Growth, 196 (1999) 41. [3] D. J. Friedman, J. F. T. Geist, S. R. Kurtz and J. M. Olson, J. Cryst., 195 (1998) 409. [4] S. I. Sato, Y. Osawa and T. Saitoh, Japn. J. Appl. Phys. Part 1-Reg. Paper Notes & Rev. Papers, 37 (1997) 2671. Acknowledgment: This work was partially funded by EC BRITE EURAM III BRPR-CT98-0721 (OPTIVAN) and U. S. Department of Energy under Contract No. DE-AC03-76F00098

Thursday, Morning, May 27, 1999
Session X
Devices II

8:20 AM

Ultraviolet Detectors Based on Epitaxial ZnO Films Grown by MOCVD: *Ying Liu*[1]; Chandu R. Gorla[1]; Nuri W. Emanetoglu[1]; Shaohua Liang[1]; *Yicheng Lu*[1]; [1]Rutgers University, College of Eng., 94 Brett Rd., Piscataway, NJ 08854-8058 USA

ZnO is a wide bandgap semiconductor material, which has many applications, such as surface acoustic wave filters and acousto-optic devices. Recently, high quality ZnO films have been used as buffer layers for III-nitride growth or as an active layer to form ZnO/GaN heterostructures. The optically pumped UV laser emission has been reported in ZnO. We have grown high quality epitaxial ZnO films on R-plane sapphire substrates by MOCVD. The epitaxial relationship between ZnO film and R-sapphire substrate has been determined to be (11-20) ZnO // (01-12) Al2O3, and [0001] ZnO // [0-111] Al2O3. The ZnO-sapphire interface is atomically sharp. The metal-semiconductor-metal UV sensitive photodetectors have been fabricated. The I-V characteristics and the sensitivity spectra of the ZnO UV photodetectors were investigated. Under 5V bias, the photodetectors exhibit sharp band-edge cut off at a wavelength of 365 nm with a large photoresponsivity (~ 4000A/W).

8:40 AM

Growth and Characterization of AlN/GaN HFETs: *Andreas Eisenbach*[1]; Egor Alekseev[1]; Dimitris Pavlidis[1]; [1]The University of Michigan, Dept. of Elect. Eng. and Computer Sci., Solid State Electronics Laboratory, 1301 Beal Ave., Ann Arbor, MI 48109-2122 USA

We report on growth and characterization of AlN/GaN single- (SH) and double-heterostructure (DH) layers for use in heterostructure FETs (HFETs). Designs of this type extend the application of GaN HFETs which have so far primarily focused on AlGaN rather than AlN donor layers and single rather than double heterostructures. Layers have been grown by low-pressure MOVPE on c-plane sapphire substrates using TMGa, TMAl, and NH3 as precursors. Device structures consisted of a low-temperature grown GaN buffer layer followed by the high-temperature growth of a nid-GaN layer, a thin AlN layer in case of the SH-HFET, or a thin AlN/GaN/AlN layer combination in case of the DH-HFET, respectively. The layers had specular surface morphology and good structural and optical properties as evaluated by XRD and PL measurements. Suitable thicknesses for AlN donor and GaN channel layers were selected using mobility values obtained by Hall measurement. The combined bulk/2DEG mobility of structures with ~100Å AlN donor layer thickness was $320 cm^2/(Vs)$ with an associated n_s of $2x10^{13} cm^{-2}$. SH-HFETs were fabricated to verify the suitability of the grown layers and devices with a gate length L_g of 2mm exhibited a high transconductance of 140mS/mm and a current I_{DS} of 540mA/mm which exceeds previously reported values. Detailed analysis of material and device characteristics will be reported at the conference. Work supported by ONR under contract number N00014-92-J-1552.

9:00 AM

Optimization of Emitter/cap Growth Conditions for InGaP/GaAs HBTs with High Current Gain: *Qinghong Yang*[1]; Dennis Scott[1]; Gregory E. Stillman[1]; [1]University of Illinois, Dept. of Elect. and Comp. Eng., Rm. 150, 208 N. Wright St., Urbana, IL 61801 USA

The effect of emitter/cap growth conditions on the common emitter current gain of InGaP/GaAs HBTs grown by LP-MOCVD has been studied. This work shows that the material quality of a carbon doped base is highly dependent on the emitter/cap growth. The emitter/cap growth effectively serves as a source of thermal stress. The thermal stress on the base during the emitter and cap growth causes carbon precipitation in the base which increases the base recombination and reduces the current gain. Atomic force microscopy and transmitting electron microscopy are used the identify the carbon precipitates. Gain improvements of more than 40% have been achieved by optimizing the emitter/cap growth conditions to reduce the thermal stress. This change in the growth procedure of HBTs does not degrade the high frequency performance of the devices.

9:20 AM

Some Differences in the Properties of C and Zn-Doped GaAs IMPATT Diodes: *D. K. Gaskill*[1]; R. Holm[1]; O. Glembocki[1]; A. Allerman[2]; [1]Naval Research Laboratory, Washington, DC 20375 USA; [2]Sandia National Laboratory, Albuquerque, NM 87185 USA

Differences in the properties of C and Zn-doped GaAs impact ionization transit time (IMPATT) diodes were investigated by photoreflectance (PR) spectroscopy. Double-drift Read IMPATT structures were grown by OMVPE with the n-side Si doped; in some diodes the p drift and contact regions were doped with C whereas in the others the p drift was doped with C and the contact region was doped with Zn. Photoreflectance spectra were found to be dominated by Franz-Keldysh oscillations; etch back measurements showed that the electric field which gave rise to the PR spectra originated in the avalanche region of the diode. Using an innovative LED-based pump source for the PR measurements, the nature of the PR modulation mechanism was found to be dependent on the diffusion of photoinjected charge across several thousand angstroms from the surface to the avalanche region. The modulation frequency dependence of the PR spectra, longer photoexcited carrier lifetime for C-doped than Zn-doped samples, and overall signal intensity of the Zn-doped vs C-doped samples imply the presence of charge traps in Zn-doped samples.

9:40 AM BREAK

Thursday, Morning, May 27, 1999
Session XI
Devices III

10:00 AM

MOVPE Growth of AlGaAs/GaInP Diode Lasers: *Frank Bugge*[1]; Arne Knauer[1]; Ingrid Rechenberg[1]; Gerd Beister[1]; Juergen Sebastian[1]; Goetz Erbert[1]; Marcus Weyers[1]; [1]Ferdinand-Braun-Institut, Mats. Tech., Rudower Chaussee 5, Berlin 12489 Germany

High power diode lasers using a combination of GaInP waveguide and AlGaAs cladding layers have been grown by MOVPE. The quality of the heterojunctions between GaInP and AlGaAs strongly affects the laser properties. The effect of growth conditions on indium carry-over and As/P exchange effects will be discussed. Diode lasers with InGaAs, respectively InGaAsP, as active zone and an emission wavelength between 1060 nm and 800 nm show a performance that is comparable for AlGaAs and GaInP/AlGaAs waveguides. Distributed Bragg Reflector, Real Index Self aligned and Ridge waveguide (RW) lasers have been processed taking advantage of the high etching selectivity between GaInP and AlGaAs and the low tendency for oxidation of GaInP. Aging tests were performed for RW lasers (3 µm width, 1000 µm long). At a single-mode output power of 100 mW (40°C) the results are also comparable to AlGaAs structures. Higher output powers result in the formation of As/P intermixing zones at the heterojunctions.

10:20 AM

Optimization of GaAsP/AlGaAs Based QW-Laser Structures for High Power 800nm Operation: *A. Knauer*[1]; F. Bugge[1]; G. Erbert[1]; H. Wenzel[1]; K. Vogel[1]; U. Zeimer[1]; M. Weyers[1]; [1]FBH, Rudower Chaussee 5, Berlin D-12489 Germany

While tensile-strained GaAsP-QWs in AlGaAs waveguides are ideal for record-high output power diode lasers in the 780-715nm range, such devices in the 800nm region have higher threshold currents due to the competition between the light-hole and heavy-hole subbands. Thus advantages of the Al-free GaAsP-QWs cannot be realized in this commercially-important wavelength region. Detailed band structure analysis of GaAsP/AlGaAs QW structures however reveal that careful tuning of the active-region thickness and strain can lead to significant reduction in threshold current. Here, we present results of optimizing MOVPE-grown 800nm-emitting laser performance by varying both QW thickness and strain. Our experimental findings are in good agreement with calculations predicting an optimal QW thickness of 17nm. We further investigated the TE-to-TM polarization change (from GaAs- to GaAsP-QW) around this wavelength region and influences on far-field quality and crystal perfection for thick QWs to obtain lasers diodes with high output power in combination with high reliability.

10:40 AM

Room-Temperature Lasers with InAlGaP/InGaP Superlattice: *Russell D. Dupuis*[1]; Yuichi Sasajima[1]; Richard D. Heller[1]; David A. Kellogg[2]; Jonathan J. Wierer[2]; Nick Holonyak[2]; David T. Mathes[3]; Robert Hull[3]; [1]The University of Texas at Austin, Microelectronics Research Center, PRC/MER 1.606D-R9900, Austin, TX 78712-1100 USA; [2]University of Illinois at Urbana-Champaign, Center for Compound Semiconductor Microelectronics, 208 North Wright St., Urbana, IL 61801 USA; [3]University of Virginia, Dept. of Mats. Sci. and Eng., Thornton Hall, Charlottesville, VA 22903-2442 USA

High-power short-wavelength lasers emitting in the yellow and orange spectral regions are of potential interest for high-performance optical storage and printing applications. We have grown InAlGaP/InGaP short-period superlattices (SLs) on GaAs substrates by low-pressure metalorganic chemical vapor deposition. The SLs typically consist of ten pairs of 0.9nm InAlGaP barriers and 1.7nm InGaP quantum wells. Lattice-matched SLs emit at 300K in the spectral range l~600nm (yellow-orange). Strain compensation of the SL is used to further reduce the emission wavelength to l~580nm (yellow). SL samples are grown simultaneously on nominally (100) GaAs substrates having different vicinal orientations. We have examined the optical properties of these SLs and find that the 300K photoluminescence (PL) for SL active regions is improved with increasing substrate misorientation. Furthermore, we have found that the incorporation of a strain-modulated aperiodic superlattice heterobarrier (SMASH) on both sides of the SL active region increases the PL intensity and reduces the full-width-at-half-maximum value of the emission spectra. The optimization of these structures has led to the low-threshold pulsed optically pumped 300K laser operation of SL samples emitting at l~600nm. We will discuss the growth and optimization of the SMASH/SL structures and the use of such active regions for short-wavelength injection laser diodes.

11:00 AM

(Al)GaInP Multiquantum Well LEDs on Ge and GaAs: *Prasanta Modak*[1]; Mark D'Hondt[2]; Ingrid Moerman[1]; Peter Van Daele[1]; Piet Demeester[1]; P. Mijlemans[3]; [1]University of Gent, INTEC-IMEC, Dept. of Inform. Tech., Sint-Pietersnieuwstraat 41, Gent B-9000 Belgium; [2]Union Miniere, Dept. of Advd. Mats., c/o RUG-INTEC, Sint-Pietersnieuwstraat 41, Gent B-9000 Belgium; [3]Union Miniere, Dept. of Advd. Mats., Watertorenstraat 33, Olen B-2250 Belgium

Ge substrates have a great potential as replacement for GaAs substrates for various optoelectronic applications. Ge has almost the same lattice constant as that of GaAs and is much cheaper. We therefore have investigated the growth of (Al)GaInP on Ge and GaAs substrates by MOVPE in view of the fabrication of red and orange LEDs. For both the Ge and GaAs substrates, In incorporation in AlGaInP reduced with increasing growth temperature and higher Zn doping. Single layers and multiquantum wells of (Al)GaInP on both the substrates indicated comparable electrical and optical performances. For Zn-doped AlGaInP, there was no sign of H-passivation when a p-GaAs cap layer was grown and the AsH_3 flow to the reactor stopped at 550°C while cooling down. The first multiquantum well LEDs which have been fabricated are very promising. More details will be presented on the use of a current spreading layer for obtaining efficient light extraction.

11:20 AM

Impact of Growth Rate on the Quality of ZNS-MQW InGaAsP/InP Laser Structures Grown by LP-MOVPE: *Wilson Carvalho*[1]; Mario Tosi Furtado[1]; Ayrton Andre Bernussi[1]; Angelo Luiz Gobbi[1]; Monica Alonso Cotta[2]; [1]Fundacao CPqD/ABTLuS, GECSF, Rodovia Campinas Mogi Mirim km118, Campinas, SP 13088-061 Brazil; [2]Unicamp, LPD-DFA, Caixa Postal 6165, Campinas, SP 13083-970 Brazil

We investigated the influence of the growth rate on the quality of zero-net-strained (ZNS) InGaAsP/InGaAsP/InP MQW laser structures for 1.55mm emission grown by LP-MOVPE. The samples consist of fixed compressive strained wells (strain=+1%) and tensile strained barriers (strain=-0.5%) grown with different quaternary compositions (Eg=0.88-1.13eV). Using higher growth rates, we obtain for the first time high quality ZNS-MQW structures, regardless having constant group V composition in the wells and barriers. The samples were analyzed by X-ray diffraction, photoluminescence and atomic force microscopy techniques. The amplitude of surface modulation roughness along the [110] direction decreased from 20nm to undetectable values with increasing growth rate and/or with quaternary barrier compositions grown outside the miscibility gap. A new deep PL broad emission band strongly correlated with the onset of wavy layer growth is also reported. Broad area and ridge waveguide lasers with 10 wells exhibited low losses (3 cm-1/well) and low threshold current densities at infinite cavity length (100 A.cm-2/well).

11:40 AM CLOSING REMARKS