1998 Electronic Materials Conference

TECHNICAL PROGRAM

University of Virginia · Charlottesville, Virginia · June 24 - 26, 1998

*** Indicates *Invited** **+ Indicates Student Paper**

Wednesday, June 24, 1998

EMC PLENARY LECTURE/STUDENT AWARDS

Ceremony: 8:30 AM

Room: 402, Chemistry Building

Session Chairman: Thomas Kuech, University of Wisconsin, Dept. of Chemical Engineering, Madison, WI 53706

Plenary Speaker: Laurence Eaves, University of Nottingham, Dept. of Physics, Nottingham, NG7 2RD UK

Topic: "Superlattices and Resonant Tunnelling: A Quarter-Century Overview"

BREAK: 9:30 AM - 10:00 AM

WEDNESDAY AM

June 24, 1998

Session A. Novel Contacts and Low Temperature - Grown Materials

Room: E303
Location: Thornton Hall

Session Chairs: Len Brillson, The Ohio State University, 205 Dreese Lab, Columbus, OH 43210-1272 USA; Suzanne Mohney, Penn State, University Park, PA 16802

10:00 AM, A1+

Studies of Schottky Barrier Height of $Ga_xIn_{1-x}P$ ($0 \le x \le 1$) For HFET Applications: H. C. KUO[1]; H. Hsia[1]; D. Caruth[1]; B. G. Moser[1]; Z. Tang[1]; S. Thomas[1]; M. Feng[1]; G. E. Stillman[1]; C. H. Lin[2]; H. Chen[2]; [1]University of Illinois at Urbana-Champaign, Electrical and Computer Engineering, Microelectronics Laboratory, Urbana, IL 61801 USA; [2]University of Ilinois at Urbana-Champaign, Materials Research Laboratory, Urbana, IL 61801 USA

The incorporation of an InGaP Schottky barrier enhancement layer (SBEL) is very attractive for the InP based MESFET and HFET applications since $Ga_xIn_{1-x}P$ ($0 \le x \le 1$) have energy gaps covering the range from 1.35 to 2.24eV at room temperature and a conduction band discontinuity of GaInP/InP ($\Delta Ec = 0.8 \Delta Eg$ for GaP on InP) is favorable for SBEL. Also there are no DX centers in GaInP. The performance of InP FETs strongly depends on the optimization of the gate contact. Knowledge about the dependence of the Schottky barrier heights on the material composition of GaInP is very important. However, to the best of our knowledge, a systematic study of the Schottky barrier heights of GaInP on InP for varying gallium composition has not been reported in the literature. In this talk, we presents a study of Schottky barrier heights for GaInP ($0 \le x \le 1$) on InP using both I-V, I-V-T and C-V measurements. The device performance of InGaAs/InP HFETs utilizing GaInP SBEL will also be discussed. All layers structure were grown by GSMBE on InP substrates using In and Ga as group III sources and AsH_3 and PH_3 as group V sources. For C-V measurements, 0.5 μm thick Si-doped (4-6X10^{17} cm^{-3}) GaInP samples with various Ga composition (0, 0.2, 0.3, 0.4, 0.5) were grown. Metamorphic buffer layers were grown on the InP substrate to reduce threading dislocations and improve the measurement reliability, even though C-V technique is not very sensitive to defects. The barrier heights were determined from the intercept voltages of the $(A/C)^2$-V plots. The compositional variation of the barrier heights for Au/GaInP/InP obtained from C-V measurements is nearly identical to that of the conduction-band offsets for InGaP/InP heterointerfaces. This result is consistent with the metal-induced gap states (MIGS) model of the Schottky barrier formation. Another series of samples of undoped $Ga_xIn_{1-x}P$ (x=0.2, 0.3, 0.4, 0.5,1) were grown on InP substrates for I-V measurement. The thickness of all GaInP SBELs was below critical layer thickness to prevent dislocation induced leakage current (no dislocations were observed by TEM). Using the thermionic-emission current equation and these characteristics, the effective barrier height was estimated to be in the range from 0.65 to 0.81 eV (ideality factors 1.01~ 1.3). This values are much lower than the data obtain from C-V measurements because the tunneling current increases as the thickness of the GaInP layer is decreased. We have designed and fabricated 0.25 μm gate-length InGaAs/P doped channel HIFETs utilizing 150 A $Ga_{0.2}In_{0.8}P$ SBEL. These devices show very good DC and RF performance. The extrinsic transcondance is 665 mS/mm. The f_{max} was 168 GHz and the f_T was 117 GHz. These results are comparable with InAlAs/InGaAs HEMTs which indicate the GaInP is a promising material for replacing InAlAs as gate SBEL material for InP based HFET applications.

10:20 AM, A2+

Reliability Studies on InAs/GaP and Au/Ti/GaP Schottky Diodes: J. JEON[1]; E. H. Chen[1]; V. Gopal[1]; E. P. Kvam[1]; J. M. Woodall[1]; [1]Purdue University, School of Engineering and NSF-MRSEC for Technology-Enabling Heterostructure Materials, West Lafayette, IN 47907-1289 USA

Schottky rectifiers have been widely utilized in semiconductor industry. Typically, these diodes consist of a metal in contact with a semiconductor material. However, thermal stability has been an important issue on these metal-semiconductor devices because of the metallurgical changes that can occur at the interface during any kind of intentional or unavoidable heat treatments. Recently, Chen et al reported that direct growth of InAs on GaP has shown promise as a Schottky diode. The resulting I-V characteristics showed low leakage currents and high breakdown voltages in reverse bias region and nearly ideal, Schottky-barrier like, forward bias characteristics with ideality factors of 1.1 or less. Since InAs/GaP junction has a large lattice mismatch (~11%), we expect that this mismatch could suppress the atomic inter-diffusion across the interface between InAs and Gap and hence reduce the mutual solubility of InAs and Gap. In this paper we discuss device reliability under thermal stress. Samples were prepared by Molecular Beam Epitaxy. After growth of a lightly doped (n=1E17) GaP layer, a thin heavily-doped (n=1E19) InAs layer (300 A) was deposited directly on GaP buffer. A thick heavily doped $In_{0.8}Ga_{0.2}As$ layer was grownon top for the purpose of making ohmic contact by AuTi evaporation. The device active region is at the InAs/GaP heterojunction. For comparison, metal-semiconductor Schottky diodes were fabricated by evaporating Au/Ti metal films on MBE grown GaP (1E17) materials. Both InAs/GaP and Au/Ti/GaP devices were annealed under a nitrogen ambient at various

temperatures for 5 hours. The results showed that the electrical behavior of the InAs/GaP Schottky diodes is not adversely affected by thermal stress up to 300ϒC. In fact, the devices exhibit an order of magnitude decrease in the reverse leakage current and have a higher breakdown voltage. On the other hand, we have observed that AuTi/GaP metal-semiconductor diodes begin to show severe degradation at 200ϒC in both forward and reverse bias regions. The better reliability of the InAs/GaP Schottky diodes is attributed to the large lattice mismatch which reduces the solubility of InAs and GaP. The results of thermal stress at higher temperatures and a burn-in test (stressed by temperature and current simultaneously) will also be presented and related to the microstructure at the interface.

10:40 AM, A3+

High Performance Hall-Sensor Devices Based on III-V Heterojunction Contacts and Materials: Z. DUAN[1]; D. T. McInturff; E. H. Chen[1]; J. M. Woodall[1]; S. Li[2]; V. Souw[2]; M. W. Elfresh[2]; [1]Purdue University, School of Electrical Computer Engineering, West Lafayette, IN 47907 USA; [2]Purdue University, Department of Physics, and the NSF-MRSEC for Technology-Enabling Hetrostructure Materials, West Lafayette, IN 47907 USA

The AlGaAs/GaAs based 2-Dimensional Electron Gas (2DEG) structure has long been known as the ideal structure for high sensitivity Hall-sensor devices due to the high electron mobility, low sheet carrier concentration, and well-confirmed conducting channel. However, the lack of temperature-cycling reliability has greatly hampered its large scale industrial application. Exploratory work has been carried out to solve this problem in two different ways. One is by utilizing a new non-alloyed contact scheme to achieve a better and more stable contact to the 2DEG structure. Another way is to study a totally new material system. We have chosen the highly mismatched InAs/GaP heterostructure, which is much easier to make ohmic contact with, and also promises less temperature sensitivity. Initial results show that the contact resistance is significantly reduced by using a heavily Si doped InAs layer on top of the AlGaAs/GaAs 2DEG structure and the sensitivity figure-of-merit is increased by more than 10% at low temperatures. Most importantly, the reliability is greatly improved under temperature cycling from 5-300K. Although the sensitivity of preliminary InAs/GaP Hall sensors is somewhat lower than that of the 2DEG devices, due to the higher sheet carrier concentration within the InAs layer, the sensitivity vs. temperature dependency of the InAs/GaP sample is much lower (better!) than that of the 2DEG structure between 5 and 300K. This is due to the fact that there is less sheet carrier concentration variation (hence, Hall coefficient variation) with temperature for the InAs/GaP structure than that for the 2DEG structure. The reason for this difference will be discussed at the conference. The device performance reproducibility is also better for the InAs/GaP sample. Device reliability testing is under way; reliability is the area where InAs/GaP devices are expected to have the biggest advantage over its 2DEG counterpart. If high reliability is in fact realized, it will open a whole new area of application for highly mismatched heterojunction systems.

11:00 AM, A4+

Low Temperature GaAs-Based Nonalloyed OHMIC Contacts as Planar Injectors for Devices: H. J. UENG[1]; V. R. Kolagunta[1]; D. B. Janes[1]; K. J. Webb[1]; D. T. McInturff[1]; M. R. Melloch[1]; J. M. Woodall[1]; [1]Purdue University, School of Electrical and Computer Engineering, West Lafayette, IN 47907 USA

Conventional Au/Ge/Ni alloyed contacts to n-type GaAs provide contact resistivity typically in the 10-6 Q-cm2 range. The alloyed metals spike nonuniformly into GaAs, leading to a poorly controlled metal/semiconductor interface [1]. To insure that the contact metals do not damage/interact with the quantum heterostructures, these device layers are typically located hundreds of nm from the surface. Ex situ Au/Ti nonalloyed ohmic contacts for n-type and p-type GaAs using a low-temperature-grown (LTG) GaAs cap layer with contact resistivity in the mid 10^{-7} Ω-cm^2 have been studied [2]. Annealing stability and device applications, including a nonalloyed GaAs MESFET, of the Au/Ti nonalloyed ohmic contacts on a LTG GaAs cap layer have also been reported with good results [3,4]. In this study, we have developed device structures which utilize the Au/Ti/LTG:GaAs nonalloyed ohmic contact in much closer proximity to the device active region than is feasible using alloyed contacts. Since the flatness of the metal/semiconductor interface is essentially set by the epitaxial layer growth, the contact structure should be essentially a planar injector. Therefore a new class of devices with shorter separation between the heterostructure and contacts can be fabricated to study the intrinsic and as-grown device properties as well as the interference between the heterostructure and contacts. We have developed a double-barrier resonant tunneling diode (RTD) with separation between the top barrier and the contact metals being less than 3Onm. Features observed in the device current-voltage characteristic are believed to be due to coherent interactions between the heterostructure barriers and the contact structure [4]. We are currently extending this study to develop devices which exploit this surface/heterostructure interaction, including a low turn-on voltage, high peak current density, shallow RTD and shallow single-barrier devices intended to provide an understanding of the interference between the heterostructure and contacts. The shallow contact structure allows for easy fabrication of planar devices thereby eliminating variation in conduction properties due to non-idealities like surface Fermi level pinning that are inherent in vertical sub-micron mesa like structures. These shallow RTD devices will provide a potential candidate for sub-micron devices with easily-controlled bias tuning, less power consumption, and efficient fabrication. [1] Y. A. Goldberg, Semiconductors 28, 935 (1994). [2] M. P. Patkar, el al., Appl. Phys. Lett. 66, 1412 (1995). [3) H. J. Ueng, et al., Appl. Phys. Lett. 71, 2496 (1997). [4]V. R. Kolagunta, et al., 39th Electronic Materials Conference, Ft. Collins, CO, June 25-27, 1997

11:20 AM, A5

Ultrafast Carrier Lifetimes and Electronic Compensation in Low Temperature Grown Be-Doped InGaAs: STEPHEN E. RALPH[1]; B. R. WASHBURN[1]; S. S. Prabhu[1]; G. Dagnall[2]; T. Kim[2]; C. Yi[2]; K. Lee[2]; E. Roberts[2]; T. Brown[2]; G. May[2]; R. Metzger[2]; A. Brown[2]; [1]Emory University, Physics, 1510 Clifton Rd, Atlanta, GA 30322 USA; [2]Georgia Institute of Technology, Department of Electrical and Computer Engineering, Atlanta, GA 30332 USA

The electronic and optical properties of low temperature grown (LTG), nominally lattice-matched, InGaAs on InP are reported. High optical quality epitaxial InGaAs with a prescribed resistivity and carrier lifetime is highly desirable for ultrafast device applications. Although LTG-GaAs is an established technique for producing these desirable qualities, the narrow gap InGaAs results in heavily n-type material which does not become semi-insulating upon anneal in contrast to GaAs. Low-temperature InGaAs:Be growth was characterized via a designed experiment in which As-pressure, growth temperature, Be-doping and post-growth anneal conditions were varied. In all, 54 distinct growth/anneal conditions were examined. Growth was performed on epi-ready InP(100) substrates, Indium mounted to Molybdenum blocks, in an all solid source Riber 2300 MBE system. The growth rate for all layers was 1 micron per hour performed under an As_4 beam equivalent pressure of either 15 or 30 microTorr. Be cell temperatures of 865, 840 and 780 ϒC were used in this experiment which nominally produce p-type doping levels in InGaAs of $1.0x10^{19}$, $2.5x10^{18}$ and $3x10^{17}$ cm^{-3}, respectively. The nature of the electronic defects and the subsequent effects on the electronic and optical properties were characterized by multiple techniques. The picosecond capture dynamics of the impurity levels associated with the deep donor levels were characterized by direct observation of the electron lifetime via time-resolved terahertz spectroscopy. Structural properties were investigated via X-ray diffraction. Temperature-dependent Hall and linear band edge absorption spectroscopy was also performed. To understand the carrier lifetime and mobility our data was used to train back-propagation neural networks. Using the neural process models, the effect of growth conditions on material properties can be visualized using 3-D contour plots. We found a complex relationship between the carrier lifetime and the growth conditions. We confirmed, for all growth conditions investigated, that Be-doping shortens the carrier lifetime and maintains the LTG-induced carrier lifetime reduction following anneal in contrast to undoped LTG material. Importantly, the carrier lifetimes were systematically longer for the material grown at the increased As-pressure of 30 microTorr. The effects of increased Be-doping and higher As-pressure were smaller on materials annealed at 600ϒC as compared to the as-grown and 500ϒC annealed material. The results of the Hall measurements revealed that LTG-InGaAs:Be was primarily p-type. For a given Be-doping and As-pressure, the material was most strongly p-type at the intermediate growth temperature 350ϒC. N-type material was produced only at the lowest growth temperature 225ϒC. The dominant growth condition affecting carrier concentrations and lifetime was the growth temperature. We explain the behavior of the Be-doping in terms of a compensation effect, however, some observations suggest the need for additional mechanisms. For example, the Be related defect may act in the form of a Be-As complex and/or may prevent precipitates from being formed.

11:40 AM, A6

MBE Growth and Characterization of C-Doped LT-GaAs: W. K. LIU[1]; K. Bacher[1]; F. J. Towner[1]; T. R. Stewart[1]; [1]Quantum Epitaxial Designs, Inc., 119 Technology Drive, Bethlehem, PA 18015 USA

GaAs grown at low temperature (LT-GaAs) using molecular beam epitaxy (MBE) contains a high concentration of excess As which gives rise to ultra-fast carrier-trapping time and excellent radiation hardness [1]. Most of this excess As in as-grown layers is in the form of As_{Ga} antisite defects, of which only approximately 1% are ionized. Thermal annealing can result in a dramatic decrease in As_{Ga} concentration, accompanied by out-diffusion of excess As into adjacent layers. The benefits of LT-GaAs buffer layers for device isolation and increased radiation hardness can thus be realized only if their thermal stability can be improved. Recently, it was found that doping the LT-GaAs layers with Be (LT-GaAs:Be) can thermally-stabilize As_{Ga} antisite defects and increases their incorporation [2,3]. These observations have been partly attributed to strain compensation whereby the lattice expansion from As_{Ga} defects is counteracted by the lattice contraction from Be incorporation [2]. However, Be is known to be mobile at high temperatures and LT-GaAs:Be may suffer from undesirable concentration-dependent diffusion at high doping levels. Carbon has been demonstrated as an attractive p-type dopant in GaAs due to its low activation energy, low diffusion coefficient, good electrical activity, and high solid solubility [4]. Due to the smaller tetrahedral covalent radius of C compared to Be, the change in lattice constant is greater in GaAs:C films than in GaAs:Be. For a given doping level, strain compensation can thus be achieved in LT-GaAs:C grown at lower temperatures (higher As antisite defect densities). Using a custom-designed CBr_4 source, we have achieved close to 100% electrical activation of C atoms in GaAs(100) layers doped between 10^{17} and 10^{20} cm^{-3}, with low H and Br background. In this presentation, we report on the use of C dopant in LT-GaAs. HRXRD, SIMS and electrical characterization results, as well as the effect of LT-GaAs:C buffer layers on the electrical properties of HEMT structures grown on top will be discussed. [1] H. Sakaki, in R.J. Malik (ed.) III-V Semiconductor Materials and Devices, North Holland, Amsterdam, p.217 (1989). [2] P. Specht, H. Sohn, M. Luysberg, A. Prasad, J. Gebauer, R. Krause-Rehberg and E.R. Weber, Proc. 19th Intl. Conf. on Defects in Semiconductors (ICDS-19), Aveiro, Portugal, July 1997 (in print). [3] M.R. Melloch et al., J. Appl. Phys. 72, 3509 (1992) and N. Atique et al., J. Appl. Phys. 77, 1471 (1995). [4] T.F. Keuch and J.M. Redwing, J. Crystal Growth, 145, 382 (1994).

Wednesday AM, June 24, 1998

Session B. Lateral Epitaxial Growth of Nitrides

Room: 203
Location: Physics

Session Chair: J. Richard Shealy, Cornell University, Dept. of EE, Ithaca, NY 14853 USA

10:00 AM, B1

Effect of V/III Ratio on Lateral Epitaxial Overgrowth of Gallium Nitride by MOVPE: J. P. IBBETSON[1]; H. Marchand[1]; P. Fini[2]; X. H. Wu[2]; S. Keller[1]; S. P. DenBaars[2]; J. S. Speck[2]; U. K. Mishra[1]; [1]University of Callifornia, Department of Electrical & Computer Engineering, Santa Barbara, CA 93106 USA; [2]University of California, Materials Department, Santa Barbara, CA 93106 USA

Lateral epitaxial overgrowth is a very promising technique to reduce the density of extended defects in GaN films, which should be beneficial for both electronic and optoelectronic devices. We have grown GaN on SiO_2-pattemed GaN/Al_20_3 substrates by low pressure-MOVPE using a close-spaced vertical reactor. Patterns consisted of 5-10 4 μm-wide stripes with a 0.01-0.5 fill factor (ratio of stripe width to pattern period), aligned along a <1-100> direction. Here we report on the morphology and structural properties of the overgrown GaN as a function of the local V/III ratio, which depends on the pattern fill factor as well as the reactor flow rates due to high surface mobility conditions that are used for the growths. By changing the local V/III ratio, the overgrown material can be made to have any of the following shapes: (i) a rectangular cross-section with sidewalls parallel to the stripe pattern; (ii) a rectangular cross-section with sidewalls faceted at ±30Ỳ to the stripes; (iii) triangular cross-section with straight sidewalls. A mixture of the different morphologies is also occasionally observed, presumably due to an evolving local V/III ratio as the mask region is overgrown. A quantitative study of lateral and vertical growth rates as a function of growth conditions will be presented, with a focus on optimizing lateral growth rates to obtain high quality coalescence of adjacent overgrown regions. We have also studied the structural properties of the different types of overgrown material. Microscopy studies show that for certain growth conditions the overgrown material is nearly free of extended defects. In particular, the density of pure screw and mixed-type threading dislocations that intersect the surface is 3-4 orders of magnitude below the ~$4x10^8$ cm^2 typically observed in bulk GaN. However, a significant - albeit relatively low compared to bulk GaN - density of pure edge dislocations exists in the overgrown GaN whose origin will be discussed.

10:20 AM, B2

Growth and Properties of Lateral Epitaxial Overgrown III-N Materials by Metalorganic Chemical Vapor Deposition: JOONGSEO PARK[1]; Paul A. Grudowski[1]; Christopher J. Eiting[1]; Russell D. Dupuis[1]; [1]The University of Texas at Austin, Microelectronics Research Center, PRC/MER 1.606D-R9900, Austin, TX 78712-1100 USA

The growth features and the optical and electrical characteristics of GaN films obtained by selective-area and subsequent lateral epitaxial overgrowth (SALEO) using metalorganic chemical vapor deposition (MOCVD) are described. The layers of this study are deposited on thin GaN substrate films that have been grown on sapphire substrates. The layers are grown in an EMCORE D125 low-pressure MOCVD system at a pressure ~100 Torr and at temperatures in the range 1030°C < Tg < 1100°C. Hydrogen is used as the main process gas and the carrier gas for the metal alkyls. Ammonia is used as the N source. Trimethylgallium (TMGa), and trimethylaluminium (TMAl) are used as Column III precursors and a V/III ratio ~2,500-5,000 for most of this work. The GaN heteroepitaxial substrates are prepared by growing ~2 μm of GaN on (0001) sapphire by MOCVD at Tg ~1050°C. Next, an ~100 nm thick SiO_2 mask is deposited by plasma-enhanced chemical vapor deposition (PECVD) using SiH_4 and N_2O precu rsors. Conventional optical lit hography and wet chemical etching are used to produce various stripe patterns in the SiO2 mask layer. To study the orientation and fill-factor dependence of the growth characteristics of this process, 3mm wide radial line stripes are indexed at 2° angular intervals relative to the GaN crystallographic axes and the ratio of open to masked area varies linearly along the stripe. Linear stripe masks with various fill factors and orientations are also used. The surface kinetics of the MOCVD process result in lateral growth of single-crystal GaN over the mask. The dependence of the physical and optical characteristics of the SALEO structures upon the growth conditions, e.g., growth temperature, growth pressure, growth rate, V/III ratio, will be described. The lateral-to-vertical relative growth rate depends upon the orientation of stripe openings, the fill factori.e., the ratio of the open stripe width to the masked stripe width, and the growth conditions. The specific orientations of the facets on the sidewalls of the laterally growing stripes are also dependent upon the growth conditions and the orientation of the mask stripes. We describe the dependence of the lateral growth rate on the growth conditions and the masked-to-open ratio. The surface morphology of the epitaxial films are characterized by scanning electron microscopy (SEM), and atomic-force microscopy (AFM). Scanning cathodoluminescence (CL) emission studies have also been performed to examine the spatial distribution of the luminescence. The morphology and luminescence intensity of the GaN layers indicate that improved materials are grown over the oxide mask. TEM analysis of SALEO films confirms that there are no threading dislocations are present in this material. We will also describe the optical and electrical characteristics of the SALEO films and InGaN quantum wells grown on these composite substrates.

10:40 AM, B3

Study of the Epitaxial-Lateral-Overgrowth (ELO) Process for GaN Using Scanning Electron Microscopy and Monochromatic Cathodo-luminescence: M. A.L. JOHNSON[1]; Zhonghai Yu[1]; T. McNulty[1]; J. D. Brown[1]; J. W. Cook[1]; JAN F. SCHETZINA[1]; [1]North Carolina State Univ., Box 8202, Raleigh, NC 27695-8202 USA

Growth of GaN by MOVPE on mismatched substrates such as sapphire or SiC produces a columnar material consisting of many hexagonal grains ~1 micron or less in diameter. However, the epitaxial-lateral-overgrowth (ELO) process for GaN creates a new material — single-crystal GaN. We have studied this process using an MOVPE reactor featuring vertical gas flows and fast substrate rotation. First, GaN/sapphire layers ~1 micron thick were grown using the standard two-temperature GaN film growth technique. The wafers were then removed from the reactor and coated with ~100 nm of SiO_2. Next, a mask set was employed to define a series of parallel SiO_2 stripes along [1-100] separated by VIAs (windows) using standard photolithographic techniques. Reactive ion etching was then used to remove the SiO_2 from the window areas and expose the underlying parallel GaN stripes. Several different window and SiO_2 stripe widths were investigated. The wafers were then returned to th e MOVPE reactor where ELO growth of GaN was initiated. A series of samples was synthesized which show ELO of GaN from its initial stages where the ELO process begins at the edges of the SiO_2 stripes to its final stage where complete coalescence of adjacent ELO layers occurs near the centers of the SiO_2 stripes. SEM images show that the (0001) GaN surface remains very flat as the ELO process proceeds with the lateral growth front consisting of {1-101} planes. Cathodoluminescence images at 590 nm clearly show the spotty deep-level emission from the columnar GaN as it emerges from the window areas. In addition, very bright deep-level emission occurs as the ELO process begins. We believe that this deep-level CL emission is associated with the strain field that accompanies the conversion of columnar GaN into single-crystal GaN via the ELO process. As the growth of GaN continues to spread laterally onto the SiO_2 stripes, the deep-level luminescence completely disappears and is replaced with pure band-edge CL at ~365 nm. This em ission occurs in the lateral overgro wth region beyond the strain field and is maintain throughout the remainder of the ELO process until coalescence of adjacent ELO layers occurs near the centers of the SiO_2 stripes. Thus, CL dominated by pure band-edge emission is the optical signature of this new single-crystal GaN material.This work was supported by Cree Research and by DARPA, ONR, and ARO contracts.

11:00 AM, B4

GaN Growth on Patterned GaN Substrates by Halide Vapor Phase Epitaxy: RONG ZHANG[1]; Ling Zhang[1]; Darren M. Hansen[1]; Thomas F. Kuech[1]; [1]University of Wisconsin, Department of Chemical Engineering, 1415 Engineering Drive, Madison, WI 53706 USA

GaN growth on patterned GaN 'substrate' by halide vapor phase epitaxy (HVPE) has been investigated in this paper. The GaN 'substrate' is a pre-metalorganic vapor phase epitaxy grown GaN film on a (0001) sapphire substrate covered with a ~100nm thick patterned SiO_2 layer. The pattern consists of many ~5.3 micron wide radial stripes exposed to the growth ambient with 0.74 degree angle separation. GaN are grown by HVPE under conventional conditions. The epitaxially lateral overgrowth of GaN on SiO_2 areas has been observed and studied. Microscopic observation reveals that the ridges along [11-20] directions have the smoothest boundaries while those around [1-100] orientations have much rougher boundaries. No significant difference of the bottom width between ridges due to different orientations is observed. All the 'free' growth fronts at the ends of stripes have very regular geometric shape. Three outside boundaries are parallel to {1-100} directions. The cross-sections of grown ridges indicate directly that the angle between the sidewalls of [11-20] ridges and the substrate surface is 61.9°, implying that the most stable GaN growth front planes are formed from the set of {1-101}. The cross-section shape of the ridge is dependent on the stripe-width and growth time. It is a triangle if the growth time is relatively long, or the top of the ridges may be flat and parallel to the substrate before that stage, implicating that (0001) is the second stable growth front in this case. If the growth time is long enough, the coalescence between neighboring overgrown facets occurs and develops a flat surface. The development of specific facet is related to existing heuristic model based on the GaAs HVPE growth system.

11:20 AM, B5

Crystalline Structure of Laterally Overgrown GaN Layers: Z. LILENTAL-WEBER[1]; J. Washburn[1]; J. Park[1]; P. A. Grudowski[2]; C. J. Eiting[2]; R. D. Dupuis[2]; [1]Lawrence Berkeley National Laboratory, Materials Science Division, 62-203, Berkeley, CA 94720 USA; [2]The University of Texas at Austin, Microelectronics Research Center, Austin, TX 78712-1100 USA

Transmission electron microscopy was applied to study the structure of GaN films grown by selective-area lateral epitaxial overgrowth (SALEO). The GaN SALEO layers are grown by MOCVD on GaN heteroepitaxial films previously grown on (0001) sapphire with a thickness of about 2000 nm. Silicon dioxide (SiO_2) 100 nm thick was used as the mask material for selective area growth. These masks were patterned with parallel and concentric stripes. Most parallel stripes vere along the [1-100] direction. Different shapes of GaN stripes and different growth rates on the c and a plane were observed. The shape of the overgrowth was most probably related to local inhomogeneities which influenced relative growth rates in "z" and "c" directions. The ratio of the lateral to that along the c direction was about 1.6 for the rectangular stripes. In the areas between masks (homoepitaxial growth about 4.6 μm wide) threading dislocations were visible with the dislocation density in the range of $7x10^8$ cm^{-2}. Plan-view and cross-section TEM observations from the layer adjacent to the sapphire substrate show a high density of nanotubes. For areas above the SiO_2 mask (6.9 mm), no straight threading dislocation along the c axis were observed. Typical defects in the overgrown areas are planar defects such as faulted prismatic dislocation loops and stacking faults. They are all formed on the c planes and their density is in the range of 10^9-10^{10} cm^{-2}. These defects are similar to the defects observed in bulk GaN platelets grown from a Ga melt under a high hydrostatic pressure of nitrogen. Because of the high growth rate in the lateral direction ("a" direction) a small growth fluctuation due to accumulation of point defects can lead to the formation of stacking faults on the c plane or formation of prismatic dislocation loops on these planes, This high growth rate in the a direction prevents formation of straight threading dislocations and the formation of pinholes. Pinhole defects were observed in the center of rectangular islands in the areas where two overgrown fronts meet each other at about 10 nm above the oxide. These pinholes in the majority of cases were overgrown. Some misorientation between the two meeting growth fronts were observed resulting in small angle grain boundaries and dislocations. Beside the planar defects on the c plane, helical dislocations were observed in the overgrown areas with axis oriented along the c direction. Accumulation of point defects could induce climb of straight dislocations with a screw component to form helical dislocations by climb motion. Since these samples were not annealed after growth, it is believed that these point defects are formed during growth and that they subsequently condense on dislocations during cooling from the growth temperature.

11:40 AM, B6

Properties of Selectively Grown Homoepitaxial GaN Layers for Electronic Application: JAIME A. FRETAS[1]; Ok-Hyun Nam[2]; Tsvetanka S. Zheleva[2]; Robert F. Davis[2]; Genardi V. Saparin[3]; Serge K. Obyden[3]; [1]Naval Research Laboratory, Electr. Science and Tech. Division (Code 6877), 4555 Overlook Ave. S.W., Washington, D.C. 20375-5347 USA; [2]North Carolina State University, Dept. of Materials Sc. and Eng., Box 7907, Raleigh, NC 27695-7907 USA; [3]Moscow State University, Dept. of Physics, Moscow 119899 Russia

Recent advances in heteroepitaxial growth of GaN have made it possible to deposit electronic grade films on various substrates. Although the fabrication of electronic and opto-electronic devices using state-of-the-art GaN films has been realized, the performance of these devices are still strongly limited by material properties. The high density of dislocations and the lack of control in doping/compensation seem to be directly and/or indirectly associated with the film-substrate lattice mismatch and/or thermal expansion coefficient mismatch. In order to reduce the usual high density of structural defects in hetero-epitaxial layers, we have deposited GaN layers on stripe-patterned GaN substrates. Overgrown layers oriented along <1 1 -2 0> and <1 -1 0 0> have triangular and rectangular cross-sections, respectively. TEM studies of the rectangular layers have shown that the dislocations present in the underlining substrate propagate only through the regrown region directly above the substrate, while the lateral overgrown region have a substantially reduced density of threading dislocations [1]. Spatially resolved room temperature Raman scattering (RS) performed on the GaN substrate and on the epitaxial layer, for laser incidence perpendicular and parallel to the epilayer, are consistent with lower biaxial strain and structural defect concentration in the lateral epitaxial overgrown (LEO) layers [2]. Low temperature photoluminescence (PL) spectra of the epitaxial region and the GaN substrate indicate that a donor-acceptor pair emission band with zero-phonon line at 3.263 eV, associated with a shallow-donor shallow-acceptor recombination process, is present only in the LEO region. Room temperature cathodoluminescence color imaging studies carried out on different samples support this observation [3]. High-resolution 6K PL spectra of the bandedge emissions show the free-exciton line and at least two shallow donors. The first at ~ 3.4667 eV is the pervasive native donor commonly observed in undoped films. The second at ~ 3.4643 eV we assign to Si- impurities, based on our

previous work [4]. This Si-doping may originate from incorporation of the thermally released Si-ions from the SiO_2 mask used to substrate patterning. The broadening and shifts observed in the bandedge emission are in agreement with the RS observation. 1. O.H. Nam, M.D. Bremser, T.S. Zheleva, and R.F. Davis, Appl. Phys. Lett., 71 2638 (1997). 2. J.A. Freitas, Jr., O.H. Nam, T.S. Zheleva, and R.F. Davis, J. Crystal Growth, accept for publ. 3. J.A. Freitas, Jr., O.H. Nam, R.F. Davis, G.V. Saparin, and S.K. Obyden, Appl. Phys. Lett., submitted. 4. J.A. Freitas, Jr., K. Doverspike, and A.E. Wickenden, Mat.Res. Symp. vol. 395 (1996) p. 485.

Wednesday AM, June 24, 1998

Session C. Materials Integration: Epitaxial Oxide

Room: 011
Location: Olsson Hall

Session Chairs: Jim Speck, University of California, Santa Barbara, CA; B. W. Wessels, Northwestern University, Evanston, IL 60208

10:00 AM, C1*Invited

The Growth of Titanate Perovskites with Unit Cell Precision by MBE: D. G. SCHLOM[1]; C. D. Theis[1]; J. H. Hanei[1]; G. W. Brown[2]; M. E. Hawley[2]; J. C. Jiang[3]; X. Pan[3]; [1]Penn State University, Department of Materials Science and Engineering, University Park, PA 16802-5005 USA; [2]Los Almos National Laboratory, Center of Materials Science, Los Almos, NM 87545 USA; [3]University of Michigan, Department of Materials Science and Engineering, Ann Arbor, MI USA

The broad spectrum of electronic and optical properties exhibited by perovskites offers tremendous opportunities for microelectronic devices, especially when a combination of properties in a single device is desired. Molecular beam epitaxy (MBE) has achieved unparalleled control in the integration of semiconductors at the monolayer-level; its use for the integration of perovskites with similar nanoscale customization appears promising. This talk will describe the use of reactive MBE to synthesize epitaxial films of the titanate perovskites $SrTiO_3$, $PbTiO_3$, $Bi_4Ti_3O_{12}$, and superlattices of these titanates. Using in situ atomic absorption composition control, feedback from RHEED intensity oscillations, and purified ozone as an oxidant, conditions were optimized to achieve the controlled growth of superlattices with layers as thin as a few unit cells. The ability of MBE to create metastable oxide heterostructures and select among energetically degenerate phases, e.g., $Sr_{n+1}Ti_nO_{3n+1}$ phases, will be illustrated. Structural and electronic characterization will be presented including 4-circle x-ray diffraction analysis, AFM, and high-resolution TEM images. Comparisons between the growth of compound semiconductors and oxides by MBE will be made. The ferroelectric $Bi_4Ti_3O_{12}$ films synthesized by MBE using adsorption-controlled growth conditions exhibit the lowest RBS channeling yield reported to date for films of this material. The challenges to achieving improved growth control will also be discussed.

10:40 AM, C2*Invited

Structure and Ferroelectric Properties of Single-Domain/Single-Crystal Thin Films of $PbTiO_3$: KLYOTAKA WASA[1]; Yoko Haneda[2]; Toshifumi Sato[3]; Hideaki Adachi[3]; Isaku Kanno[3]; Darrell G. Schlom[4]; S. Trolier-McKinstry[4]; Chang-Beom Eom[5]; [1]Yokohama City University, 22-2 Seto Kanazawa-ku, Yokohamashi 236 Japan; [2]RITE Institute, 9-2 Kizugawadai, Kizucho, Kyoto 619-02 Japan; [3]Matsushita Elec., Central Research Labs., Seika-cho, Kyoto, 619-02 Japan; [4]Penn State University, Materials Research Institute, University Park, PA 16802 USA; [5]Duke University, Dept. of Mechanical Eng. and Mater. Sci., Durham, NC 27708-0300 USA

Continuous single crystal $PbTiO_3$ thin films with single c-domain structure were epitaxially grown on both miscut $SrTiO_3$(001) and $SrRuO_3$(110)/miscut $SrTiO_3$(001) substrates by planar rf-sputtering for film thickness ranged from 5nm to 300nm. The miscut angle was 1.7 degree. On the miscut substrates, the film growth was governed by the step-flow growth mode and resultant film surface was atomically flat. The lattice misfit strain induced during the film growth was quenched in the film. The film lattice was tetragonally expanded (5 to 10%) due to the compressive force in the film plane. The c-lattice parameter shows no clear anomalies in the temperature range of RT to 600°C, although anomalies will be expected at FE to PE transition temperature. The dielectric measurements of $PbTiO_3$(001) thin films on the $SrRuO_3/SrTi_20_3$ substrates with gold top electrodes suggest that the Ps is 20 to 30μC/cm^2 with room temperature dielectric constant of 70 at 1KHz (loss factor < 1 %). The film shows slightly lower refractive index relative to bulk $PbTiO_3$.

11:20 AM, C3

High Temperature Stimulated Emission from MBE Grown ZnO Epitaxial: T. YAO[1]; D. M. Bagnall[1]; Y. F. Chen[1]; Z. Zhu[1]; M. Y. Shen[2]; T. Goto[2]; [1]Tohoku University, Institute for Materials Reseach, 2-1-1 Katahira, Aoba-ku, Sendai 980, Japan; [2]Tohoku University, Department of Physics, Sendai 980, Japan

We have observed stimulated emission from MBE grown ZnO epilayers up to 550 K with the emission wavelength being 2.9 eV at 550 K. The characteristic temperature for the threshold intensity was estimated to be 90 K. At low excitation powers, a free exciton emission peak was observed, while a stimulated emission peak attributed to exciton-exciton scattering emerged at higher excitation intensities. At much higher excitation regime, a second stimulated emission peak due to electron hole plasma emerged. These features could lead to the realization of ZnO-based UV excitonic devices capable of operating at high temperatures.

Wednesday AM, June 24, 1998

Session D. Nanoscale Characterization

Room: E316
Location: Thornton Hall

Session Chairs: Edward Yu, USSD, ECE Department; Julia Hsu, University of Virginia, Department of Physics

10:00 AM, D1

Strain Variations in InGaAsP/InGaP Superlattices Studied by Scanning Probe Microscopy : HUAGIE CHEN[1]; B. Grandidier[1]; R. M. Feenstra[1]; R. S. Goldman[2]; C. Silfvenius[3]; G. Landgren[3]; [1]Carnegie Mellon University, Dept. Physics, 5000 Forbes Ave., Pittsburgh, PA 15213 USA; [2]University of Michigan, Dept. Materials Science, 2300 Hayward St., Ann Arbor, MI 48109 USA; [3]Royal Inst of Technology, Dept. Electronics, Kista Sweden

InGaAsP-based multiple quantum well structures with alternating compressive- and tensile-strained layers are promising for optoelectronic device applications, such as light sources and detectors in optical fiber communications systems. Although the structures are intended to be strain-balanced, the optical properties are often degraded by residual-strain related effects which are not fully understood. We have investigated the properties of a series of "strain-compensated" InGaAsP/InGaP superlattices, grown by metalorganic vapor phase epitaxy, with and without InP interlayers inserted in the InGaP barrier. Using cross-sectional atomic force microscopy (xAFM) and scanning tunneling microscopy (xSTM), lateral variations in the thickness of the barrier and quantum well layers are seen, leading to large undulations of the (001) oriented growth front. In addition, undulations in the morphology of the (110) cross-sectional faces are observed, and are attributed to elastic relaxation of this surface due to underlying strain arising from the lateral thickness variations and associated compositional variations of the superlattice layers. Addition of InP interlayers in the middle of the InGaP barriers is found to significantly improve the growth morphology. Finite element computations are used to extract a quantitative measure of the strain variation, thereby leading to an estimate of the degree of compositional variation in the alloys. For a particular system containing 0.9% compressive strain in the quantum wells and 0.8% tensile strain in the barriers, and including InP interlayers, the resulting lateral variation of strain is found to be +/- 0.3%, leading to compositional variations of +/- 4% for purely cation segregation or +/- 25% for purely

anion segregation. The actual compositional variations will be have values intermediate between these two limits, and the results thus obtained are comparable to the few % variations in alloy composition which have been observed in other systems. We thus demonstrate the usefulness of xAFM for routine characterization of strain relaxation effects in such strain-compensated III-V semiconductor systems.

10:20 AM, D2+

Mapping Surface Contact Potential Variations on GaAs/Ge Films Using an Electrostatic Force Microscope: QIN XU[1]; Julia Hsu[1]; [1]University of Virginia, Department of Physics, McCormick Road, Charlottesville, VA 22901 USA

In addition to detecting surface topographical changes as in normal atomic force microscopes, electrostatic force microscopes (EFM) are capable of measuring variations in surface contact potential (SCP) and capacitance gradient on the sample surface. Hence, using an EFM enables us to distinguish among different defects and local changes in composition and in static charges. Here, we concentrate on EFM study of SCP variations near defects on GaAs films grown on Ge or Ge/Si substrates by molecular beam epitaxy. By applying an alternating current (AC) and a direct current (DC) voltage between the conducting tip and sample, the EFM maps out local SCP and capacitance gradient between the tip and sample simultaneously with sample topography. The EFM signal at the AC frequency (1f) is proportional to the capacitance gradient and the difference between the applied DC voltage (Vdc) and SCP, and the signal at the second harmonic of the AC frequency (2f) is proportional to the capacitance gradient only. When there are large sample topographical changes, the capacitance gradient and thus the 1f and 2f signals can be affected due to the changes in the capacitance between the sample and cantilever. However, by dividing 1f by 2f, which are taken simultaneously, we can remove this unwanted topographical effect from SCP measurements. By operating Vdc close to the averaged SCP, the 1f contrast is increased, thus improving the signal to noise ratio in SCP measurements. In addition, note that 1f signal is zero when Vdc is equal to local SCP. Consequently, the quantitative difference of SCPs at different sample positions can be measured by varying Vdc. On GaAs samples with surface anti-phase boundaries (APBs), we find that the SCP at the APBs is different from that of domains. Our measurements show that the work function at the APBs is 30 mV larger than that of the domains. In a thick film which contains buried APBs and wedge-shaped depressions on the surface, we find the work function of the wedge-shaped depressions is 25 mV smaller than that of the surrounding area. Hence, these wedge-shaped depressions have defect electronic states different from those of APBs. In addition, we find some line defects that show contrast in 1f images but no topographic changes. Furthermore, 2f images of this sample show two distinct values of capacitance on the surface, which cannot be explained by the topographical effect. This may be due to segregation of dopants or composition variations. We demonstrate the use of EFM to distinguish different types of defects by measuring variations in relative SCPs (thus the work functions or positions of Fermi level) with 5mV accuracy and 30nm spatial resolution.

10:40 AM, D3+

Cross-Sectional Kelvin Probe Force Microscopy of Epitaxial Layers for Heterojunction Bipolar Transistors: P. A. ROSENTHAL[1]; E. T. Yu[1]; R. L. Pierson[2]; P. J. Zampardi[2]; [1]University of California,San Diego, Department of Electrical and Computer Engineering and Graduate Program in Materials Science, 9500 Gilman Drive, Mail Code 0418, La Jolla, CA 92093-0418 USA; [2]Rockwell International Science Center, 1049 Camino Dos Rios, Thousand Oaks, CA 91358 USA

Heterojunction bipolar transistors (HBTs) in a variety of material systems are of outstanding current interest for a wide range of applications in high-speed and high-power electronics. Dramatic improvements in device performance may be achieved through proper design of compositional and dopant profiles within an HBT. Accurate characterization of and control over the vertical compositional and dopant profiles, which directly influence the electrostatic potential distribution within such a device, at or near the nanometer scale is essential for analysis and optimization of HBT performance. We have used cross-sectional scanning Kelvin probe force microscopy (SKPM) in air to characterize $In_yGa_{1-y}As/Al_xGa_{1-x}As$/GaAs epitaxial layer structures grown for use in HBTs. The samples studied were grown by metalorganic chemical vapor deposition (MOCVD) on semi-insulating GaAs, and consisted of the following layers (in order of growth): 200 nm n-$Al_{0.8}Ga_{0.2}As$; 600 nm n-GaAs, with donor concentration (N_D) greater than $5x10^{18}$ cm^{-3} ; 400 nm n-GaAs, $N_D=6x10^{16}$ cm^{-3}; 300 nm n-GaAs, $N_D=3x10^{16}$ cm^{-3} ; 50 nm p-$In_{0.01}Ga_{0.99}As$ with acceptor doping $N_A=4x10^{19}$ cm^{-3} ; 60 nm n-$Al_{0.25}Ga_{0.75}As$, $N_D=4x10^{17}$ cm^{-3} ; 20 nm compositionally graded n-$Al_xGa_{1-x}As$ (x=0.25-0.00), ND=$4x10^{17}$ cm^{-3} ; 120 nm n-GaAs, $N_D=4x10^{18}$ cm^{-3} ; 40 nm n-$In_yGa_{1-y}As$(y=0.00-0.60), $N_D\oplus10^{19}$ cm^{-3} ; 40 nm n-$In_{0.6}Ga_{0.4}As$, $N_D\oplus10^{19}$ cm^{-3}. Samples were then cleaved in air and SKPM measurements performed on the exposed cross-sections of the epitaxial layers. Surface potent ial images obtained from these samples reveal contrast that is qualitatively consistent with the expected work function difference between the layers. Conven,ional atomic force microscopy performed on the epitaxial layers regularly show an 80 nm wide topographic feature approximately 300 nm from the sample edge. Based on its width and location, we interpret this feature as the $A_{lx}Ga_{1-x}As$ emitter layer, which provides a spatial reference point for interpretation of the potential images. For measurements performed with relatively low AC voltage amplitude (V_{AC}= 5 V) and relatively large lift height (20 nm), the basic potential structure is clearly visible, with the n-GaAs collector region exhibiting, as expected, a smaller wo rk function than the p-$In_{0.01}Ga_{0.99}As$ base region. The n-$A_{lx}Ga_{1-x}As$ emitter region also exhibits a smaller work function than the base region. Increasing V_{AC} to 10 V at the same lift height reveals greater detail in the potential structure. The potential contrast increases between the base and collector layers. In addition, potential contrast which spatially corresponds to the collector-subcollector interface becomes visible. When the lift height is decreased to 10 nm, the base layer becomes more evident and regions of lower potential appear on either side of the base. Preliminary analysis suggests that certain features visible at large AC modulation voltages and small lift heights may also be associated with tip-induced band bending at large tip-sample voltages, which would result in variation of the tip-sample capacitance at the AC modulation frequency.

11:00 AM, D4+

Nanoscale Studies of Temperature Dependent Photocurrent in Relaxed SiGe Films: MATTHEW H. GRAY[1]; Julia W.P. Hsu[1]; [1]University of Virginia, Physics, McCormick Rd., Charlottesville, Va 22901 USA

Using near-field scanning optical microscopy (NSOM) we examine the optoelectronic properties of defects in SiGe films with ~100nm spatial resolution. These films can be used to integrate GaAs and InGaP light emitting diodes on Si and also in the fabrication of heterojunctions with high 2D electron gas mobility. Defects in the films can be detrimental to the performance of these devices. The films we studied are completely strain relaxed, exhibiting bulk $Si_{1-x}Ge_x$ optical properties. The (001) surfaces of these samples show two characteristic topographic features: pits associated with the terminations of threading dislocations and an oriented undulation, called crosshatch, caused by the underlying misfit dislocations. Our room temperature NSOM experiments have shown that threading dislocations are carrier recombination centers that suppress near-field photocurrent (NPC). It is also seen that the topographic crosshatch has a corresponding variation in NPC. To further study the optoelectronic properties of these defects we constructed a variable temperature near-field scanning optical microscope (VT-NSOM). This microscope allows us to study changes in NPC as a function of temperature. The VT-NSOM sample stage is cooled by attachment to a continuous flow cryostat via flexible copper braids and can be held at any temperature between 13 and 300K. Because the piezo scanner is not cooled significantly, the scan range of our VT-NSOM decreases by only 30% when cooling to 150K and remains approximately constant (35μm x 35μm) below 150K. At 73K we observed no appreciable drift in repeated 2.8μm x 2.8μm images. Other advantages of our VT-NSOM are its short cycle time and optical accessibility. An externally mounted optical microscope allows us to find and image specific areas of the sample at different temperatures. The probes are tapered, aluminum coated, single-mode optical fibers which act as a sub-wavelength source for 670nm light. Non-optical feedback is used to regulate the tip-sample separation during a scan, generating a topographic image. Topographic and NPC images are acquired simultaneously, enabling us to correlate surface morphology and NPC contrast of near surface defects.
We would expect changes in the carrier statistics and the carrier diffusion length as a function of temperature. For an electrically active defect such changes would be reflected in the depth of contrast and/or the measured spatial extent. We observe a large increase in the overall (spatially averaged) photoresponse with decreasing temperature. The crosshatch NPC features changes with temperature. However, by examining specific defects over the range 73K to 292K we find that the relative NPC contrast of the threading dislocations does not vary greatly. We will discuss the physical origins of the observed temperature effects.

11:20 AM, D5

Reconstruction of Three Dimensional Structure and Chemistry Using Focused Ion Beam Images And Secondary Ion Mass Spectrometry: DERREN N. DUNN[1]; Robert Hull[1]; [1]University of Virginia, Department of Materials Science and Engineering, Thornton Hall, Charlottesville, VA 22903 USA

A technique to produce three-dimensional structure and chemical maps with 10 nm resolution will be presented. A focused ion beam system is used to collect secondary electron and secondary ion mass spectroscopy (SIMS) elemental maps as a function of depth. Tomographic reconstruction techniques are then used to calculate a unique volume from these images and elemental maps. Variations in three-dimensional structure and chemistry can then be displayed using standard computer graphics methods. This technique can be used to investigate complex structures ranging in size from 100 mm on a side to 10 nm on a side, with 10 nm spatial and depth resolution. As a result, arrays of device structures can be analyzed as easily as single devices. In addition, due to the use of SIMS, chemical sensitivity to nearly all elements is possible. As an example, results from the application of this technique to re-flowed Al vias will be presented. In summary, we describe a practical, rapid technique to investigate three-dimensional nano-scale structural and chemical variations in device structures of arbitrary complexity.

11:40 AM, D6

Late News

Wednesday AM, June 24, 1998

Session E. Plasma and Ion Beam Processing

Room: 009
Location: Olsson Hall

Session Chairs: Daniel Doctor, HRL Laboratories, Malibu, CA 90265 USA; Evelyn Hu, University of California, ECE Department, Santa Barbara, CA 93106 USA

10:00 AM, E1

Low Energy Chemically Assisted Ion Beam Etching of InP/GaInAsP: C. F. CARLSTROM[1]; S. Anand[1]; G. Landgren[1]; [1]The Royal Institute of Technology, Laboratory of Semiconductor Materials, Department of Electronics, Electrum 229, Isafjordsgatan 22.26, S-16440 Kista, Stockholm Sweden

Dry etching is a key technology for fabrication of many novel electronicand optical devices. The demands on the etch process are rather high. Theprocess must provide reasonable etch rates and at the same time the damagemust be low. These requirements can be met by Ion beam methods capable oflow ion energies and high ion flux. In this work, we have investigated$N_2/CH_4/H_2$ based chemically assisted ion beam etching (CAIBE) of InP/GaInAsPusing an Inductively coupled RF plasma source. The ion energy was variedfrom 500 eV down to 75 eV. The etch rates, anisotropy, polymer formation andsurface damage were characterised. The importance of CH_4 and H_2 in the etchprocess is demonstrated by comparing the $N_2/CH_4/H_2$ and N_2/CH_4 (without H_2)CAIBE, and N-ion milling processes. The surface morphology was quantified by roughness measurements by atomicforce microscopy and the etch induced damage was characterised byphotoluminescence (PL) yield using near surface GaInAsP multiple quantumwells as probes. The wells were brought close (20 nm) to the processedsurface by etching the InP cap layer. Therefore, the PL from the QWs will besensitive to both surface damage and possible damage caused directly in thewells. The best PL intensities and extremely smooth surfaces (rms roughness < 1 nm)were obtained for 75eV $N_2/CH_4/H_2$ (5/4/14 sccm.) CAIBE. At higher energies PLintensities were lower and the surfaces were rougher (e.g. 4 nm rmsroughness for 500 eV). The rough surface morphology is attributed to animbalance between the physical and chemical components in the etch process. Compared to the wet etched control sample the PL intensity was about 7 timeslower for the 75 eV process. However, upon annealing it recovered to 50% ofthat for the control sample suggesting significant reduction in the damage. In striking contrast, the PL intensities for the higher energy processesshowed degradation after annealing. The post-anneal PL intensities appear tobe linked to the as etched surface morphologies and possible mechanisms arediscussed. Lastly, N_2 and Ar based processes are compared to understand andhighlight the role of N_2 in the etch process.

10:20 AM, E2

Bromine Ion-Beam-Assisted Etching of III-V Semiconductors: W. D. GOODHUE[1]; Y. Royter[2]; D. E. Mull[3]; S. S. Choi[1]; C. G. Fonstad[2]; [1]University of Massachusetts Lowell, Department of Physics and Applied Physics, Lowell, MA 02139 USA; [2]Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Sciences, Cambridge, MA 02139 USA; [3]Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173 USA

Bromine ion-beam-assisted etching produces smooth vertical sidewalls in GaAs, InP, AlSb and GaSb as well as in the usual alloys formed from these materials. Care must be taken, however, during etching to match the specific material system with an appropriate substrate etch temperature. For example, vertical walls were obtained using substrate temperatures in the range of 150 to 200ϒC with InP, 80 to 140ϒC with GaAs, and below 30ϒC with AlSb/GaSb. Etch rates can be varied from several nnm/min to 0.16 μm/min through the bromine flow rate, Ar+ ion beam density and energy, and the substrate temperature. The etching rate ratios of bromine-only etching (no Ar+ ion beam) to argon-ion-beam-assisted bromine etching to argon ion etching (no bromine) with an ion beam density of 40 $\mu A/cm^2$ and ion beam energy of 500 V were measured to be 11.5:23:1 and 16:125:1 at a substrate temperature of 200ϒC and 2:42:1 and 1:40:1 at a substrate temperature of 100ϒC for GaAs and InP, respectively. Such rate enhancements were found to be typical with these materials. Bromine ion-beam-assisted etching appears to have an advantage over chlorine ion-beam-assisted etching in that substrate temperature ranges can be found for which vertical sidewalls are maintaned while etching through layered structures composed of various alloys of the materials. In this talk we will present results obtained with various III-V binaries, alloys, and heterostructures. This work was sponsored by the Department of the Air Force under Contract F19628-95-C-0002. The opinions, interpretations, conclusions, and recommendations are those of the authors and not necessarily endorsed by the United States Air Force.

10:40 AM, E3

New Plasma Chemistries for Etching III-V Compound Semiconductors: BI_3 and BBr_3: T. MAEDA[1]; H. Cho[1]; J. Hong[1]; S. J. Pearton[1]; [1]University of Florida, Department of Materials Science and Engineering, Rhines Hall PO Box 116400, Gainesville, FL 32611-6400 USA

In plasma etching of III-V compound semiconductors, commonly used Cl_2-based chemistries are not suitable for In-containing materials due to low volatility of $InCl_x$ etch product. Though I_2-based chemistries are considered to be advantageous because of high volatility of InI_x, there have been no reports on the use of suitable form of I_2-source materials for high density plasma etching. In this presentation, we discuss Inductively Coupled Plasma (ICP) etching of In-compounds (InP, InAs and InSb) together with Ga-compounds (GaAs, GaP and GaSb) in two new chemistries: BI_3/Ar and BBr_3/Ar discharges, as functions of ICP source power, rf chuck power, and plasma composition. In BI_3 discharces, dc chuck self-bias decreased with increasing BI_3 content, indicating that the ion density in the plasma is increasing under these conditions, thus BI_3 is more easily ionized than Ar. This was also evidenced by the strong transitions in optical emission spectra. In-compounds gave higher etch rates than Ga-compounds due to higher volatility of InI_3 than that of GaI_3. Etch rates increased with increasing BI_3 content, indicating the presence of strong chemical component to these etching. Etch rates increased rapidly as rf chuck power was increased, and then decreased at higher powers. The increase of etch rates indicates a strong ion-assisted component to the etching and the decrease indicates that the active etching species (iodine neutral in this case) are removed by sputtering before they react with substrate atoms, as is quite common to plasma etching of III-V materials. Etch rate as high as 2 μm/min were obtained for InP while that of GaAs was 1 μm/min. In BBr_3 discharges, on the other hand, higher rf power was required to effectively remove less volatile etch products than in BI_3. The dc self-bias increased with increasing BBr_3 content, indicating it is less readily ionized than Ar, on the contrary to the case of BI_3 discharges. Etch rate as high as 2.5 μm/min were obtained for GaAs while that of InP was 2.2 mm/min. We performed AFM scans to evaluate the quality of the etched surface morphology

of InP and GaAs. For the etching in BI_3 discharges, we obtained smooth surfaces (RMS roughness < 3 nm) for both materials by choosing the etching condition. For the etching in BBr_3 discharges, we currently obtained rougher surfaces (RMS roughness < 30 nm) for InP and surfaces with similar smoothness for GaAs as compared with BI_3 etching. Surface chemistry after etching (AES) and side-wall feature (SEM) will also be presented at the conference. *Permanent address: Fujitsu Laboratories Ltd., Kanagawa, Japan

11:00 AM, E4

Dopant Profiles in Dual-Poly Gates with Buried Ultra-Low-Energy Implants: J. BENK[1]; G. Hobler[1]; D. C. Jacobson[1]; W. M. Mansfield[1]; J. Jackson[2]; [1]Lucent Technologies, Bell Laboratories, 600 Mountain Ave, Murray Hill, NJ 07974 USA; [2]Eaton Corporation, 108 Cherry Hill Drive, Beverly, MA 01915 USA

We describe a new process, suitable for fabrication of low-voltage sub-0.25micron CMOS devices with sub-micron PMOS-NMOS spacing. The gate structures are based on the concept of buried, ultra-low energy gate implants, utilizing the new generation of high-current, low-energy ion implanters. We present both simulated and experimental dopant profiles for B, As and P implanted into a-Si at 0.5 - 10keV energy range and then capped with a second layer of a-Si. The diffusion and redistribution of these "buried" dopants are strikingly different from dopant profiles in conventional polycide or salicide gates. The threshold voltage shifts due to lateral dopant diffusion between P- and NMOS devices with connected W-polycide gates, are minimized (<5-10mV) by com bining thermal treatments with blanket nitrogen gate co-implants to control dopant activation and diffusion. The reduced annealing times and temperatures for gate activation, made possible by short diffusion distances, alleviate processing problems related to dopant lateral diffusion not only in the gates but also in the device channel regions.

11:20 AM, E5

On the Choice of Excitation Frequency for Plasma-Enhanced CVD of Amorphous And Microcrystalline Silicon: RAINER PLATZ[1]; Sigurd Wagner[1]; Christian Hof[2]; Stephan Wieder[3]; Bernd Rech[3]; [1]Princeton University, Dept. of Electrical Engineering, Engineering Quadrangle, Olden Street B405, Princeton, NJ 08544 USA; [2]Universite de Neuchatel, Institut de Microtechnique, Rue A.-L. Breguet 2, Neuchatel, CH 2000 Switzerland; [3]Institut f. Schicht- und Ionentechnik, Forschungszentrum, Juelich, D 52425 Germany

Plasma enhanced chemical vapor deposition (PE-CVD) is widely used for the deposition of hydrogenated amorphous silicon (a-Si:H) and microcrystalline silicon (μc-Si:H). Recently the plasma excitation frequency has assumed renewed importance, for two reasons. One is that the a-Si:H photovoltaic and thin-film transistor industries need high deposition rates to reduce capital cost. The second is that any practical use of μc-Si:H requires much higher growth rates than obtained to date. It has been known that the plasma excitation frequency affects the film growth rate of PE-CVD deposited a-Si:H and μc-Si:H. However, it is also known empirically that raising the growth rate reduces the electronic quality of the deposited film. To resolve this question over the ent ire frequency range, we report the first comparative evaluation of DC, radio frequency (RF, 13.56 MHz), and very high frequency (VHF, 70 MHz) plasma excitation. We varied the substrate temperature between 150ºC and 350ºC and the hydrogen/silane ratio (H_2-dilution) between zero and 40. H_2-dilution has been the key to improving the quality and stability of a-Si:H, and to enabling the deposition of μc-Si:H. The optical gap of the films decreases with increasing deposition temperature, linked to a decrease of the hydrogen content from ~10-12 at.% at standard temperature (~220ºC) to ~6-8 at.% at temperatures above 300ºC. At all three frequencies H_2-dilution results in an increase of the optical gap E_{04} ($\alpha(E_{04}) = 10^4$ cm^{-1}) from ~1.9 eV to >2.05 eV for the standard deposition temperature. The hydrogen content increases with increasing H_2-dilution for VHF and RF excitation, while for DC we observe an initial drop for small dilution ratios followed by an increase at higher dilutions. VHF deposition yields the highest growth rates overall. For low H_2-dilution ratios the DC growth rates are higher than those obtained with RF excitation. At high dilution, the R F and DC growth rates become similar. The growth rate is reduced to ~2 Å/s (VHF), ~0.6 Å/s (RF) and ~0.4 Å/s (DC) for the highest H_2-dilution that still results in amorphous films. However, the optimum amount of H_2-dilution and the growth rate vary strongly with excitation frequency. A moderate amount of H_2-dilution results in amorphous films with enhanced stability against light-soaking for all three frequencies and enables us to deposit a-Si:H of good quality also at temperatures well below 200ºC. At higher H_2-dilution ratios, the stability of VHF and RF deposited films does not improve further, and the quality of DC deposited films even diminishes. μc-Si:H growth starts at H_2-dilution ratios of ~13 (VHF) and >30 (RF and DC) for standard deposition temperature. Higher substrate temperature during the deposition results in microcrystalline growth at lower H_2-dilution ratios.

11:40 AM, E6

Thermal and Electrical Through-Wafer via Hole Process for AlGaAs/GaAs Power HBTs: C. D. NORDQUIST[1]; A. Mitra[1]; D. Lubyshev[1]; M. Micovic[1]; D. Black[1]; D. L. Miller[1]; T. S. Mayer[1]; [1]Penn State University, Electrical Engineering Department, 121 Electrical Engineering East, University Park , PA 16802 USA

Use of heterojunction bipolar transistors (HBTs) in wireless and satellite communication applications requiring linear power amplification is increasing due to the excellent linearity and potential of high power density in these devices. The performance of high power devices is typically limited, however, by the thermal rather than electrical properties of the device. Processes such as flip-chip bonding, thermal shunts, and bathtub heatsinks have been studied to minimize degradation due to the high thermal resistance associated with the device and the substrate. Of these, the bathtub heatsinks hold the most promise for ease of integration into existing HBT processes. To achieve the full utility of this design, the bathtub must be etched to within 5 μm of the active layers of the HBT, which has been performed previously using selective wet etching with citric acid. Although this process can be used to reduce the thermal resistance of the device, the minimum device dimension is limited by the lateral undercut profile of the wet etch. This results in the utilization of a large chip area per device and an increase in the collector-to-ground capacitance of the HBT due to coupling between the heatsink and subcollector. In order to improve the thermal management of AlGaAs/GaAs power HBTs, we have developed a selective dry etching process using magnetically enhanced reactive ion etching (MIE) that is used to fabricate through-wafer via holes to provide a thermal and electrical shunt to the backside of the GaAs substrate. The dry etch, which uses $SiCl_4$ and SF_6, stops abruptly on AlGaAs etch-stop layers having Al concentrations that exceed 70%. Under optimized conditions of $SiCl_4$ flow rate = 20 sccm, SF_6 flow rate = 9.3 sccm, pressure = 30 mTorr, and power = 300 W, the selective dry etch has an etch rate of approximately 1.5 μ/min and produces deep (> 80 μm) via holes with smooth, nearly anisotropic sidewall profiles. Moreover, the etch rate is relatively independent of via hole dimension, making it suitable for use on through-wafer via holes with dimensions as small as 20 x 20 μm^2. This dry etch was integrated into a standard AlGaAs/GaAs emitter-up HBT process to compare device characteristics with and without a backside thermal and electrical through-wafer via holes. The HBT structure that was used had a 80-nm base doped with carbon to a concentration of 4 x 10^{19} cm^{-3}, and a 1.0-μm collector doped 2 x 10^{16} cm^{-3}. Following the standard frontside process, via holes were etched through the thinned GaAs substrate stopping selectively on an undoped AlAs etch-stop layer inserted between the n+-subcollector and the semi-insulating GaAs substrate. Once via holes were etched, the AlAs etch stop layer was removed, backside ohmic metal was deposited, and Au was plated into the via holes. Because the thermal conductivity of Au is a factor of six higher than that of the GaAs substrate, the Au plated through-wafer via holes provide a low thermal resistance shunt to the backside of the substrate. The dc characteristics of HBTs fabricated with and without through-wafer thermal and electrical via holes were nearly identical having common-emitter current gains of 70, cross-over currents of 10 nA, and common-emitter breakdown voltages of 14 V. This through-wafer thermal and electrical via hole process is also being extended to fabricate collector-up HBTs with a direct through-wafer contact to the emitter.

Wednesday AM, June 24, 1998

Session F. Novel Oxide Formation and Silicon Oxide Processing

Room: 005
Location: Olsson Hall

Session Chairs: Marian Hargis, Mellwood Laboratories, West Lafayette, IN 47906; Greg Stillman, University of Illinois, Department of Electrical Engineering, Urbana/Champaign, IL USa

10:00 AM, F1

Electrical Properties of Nanometer Oxidized Titanium Line on Atomically Flat α-Al_2O_3 Substrate: K. MATSUMOTO[1]; Y. Gotoh[1]; T. Maeda[1]; [1]Electrotechnical Laboratory MITI, 1-1-4, Umezono, Tsukuba-shi, Ibaraki-kenn, 305 Japan

The electrical properties of the nanometer wide oxidized titanium (TiOx) line were examined that sat on the atomically flat α-Al_2O_3 substrate. By heating the α-Al_2O_3 (1012) substrate up to 1000C for 1 hour, the surface of the α-Al_2O_3 substrate becomes atomically flat due to the step migration. The terrace size of the atomically flat a-Al2O3 measured by AFM is 280nm, and the step height is 0.34nm that correspond to the distance of two α-Al_2O_3 (1012) planes. The Ti metal of 2.5nm thick was then deposited by ebeam evaporator on to the α-Al_2O_3 substrate. Even after the deposition of the metal, the surface roughness of Ti metal is less than 0.15nm and retains the atomically flat condition. The electrical properties of the TiOx layer were examined by using the structure of the planar-type MIM diode. At both ends of the Ti layer in the planar-type MIM diode, the source and drain ohmic contacts made by Ti/Au were formed. At the center of the Ti layer, the TiOx line was fabricated using atomic force microscopy(AFM) nano-oxidation process, in which AFM cantilever works as a cathode, and a surface of metal is anodized to form a few tens of nanometer wide oxidized metal line. The width and length of TiOx line are 64nm and 513nm, respectively. Due to the thin Ti layer of 2.5nm, the oxidized Ti line reaches completely to the bottom of the Ti layer. The temperature dependence of the current-voltage characteristics of the planar-type MIM diode was measured at the temperature range of T= 7K to 285K and the applied voltage range of 0.1V to 10V. At the temperature less than 100K, the current shows almost no temperature dependence in the applied voltage range of 2V to 10V, that implies the current consists of the Fowler-Nordheim(F-N) tunneling current. From the F-N fitting of the current at 7K, the effective mass of the electron inside TiOx is found to be m*=0.143 and current shows the quantum interference oscillation. This is attributed to the uniformity of the oxidized line width formed on the atomically flat substrate. At the temperature higher than T=200K, the current increases drastically, meaning the onset of the thermionic emission current regime. By increasing the applied voltage, the slope of the current on the temperature decreases, meaning that the image force barrier height lowering effects occurs. From the slope of the current, the intrinsic barrier height between TiOx and Ti is found to be ϕ_{B0}=468meV.

10:20 AM, F2+

The Influence of Post-Oxidation Anneals on Ultra-Thin RTO Grown SiO_2 Gate Oxides: C. GRUENSFELDER[1]; J. Bevk[1]; D. Brasen[1]; Y. J. Chabal[1]; K. Evans-Lutterodt[1]; K. S. Krisch[1]; W. Mansfield[1]; R. L. Opila[1]; P. J. Silverman[1]; T. W. Sorsch[1]; G. L. Timp[1]; M. K. Weldon[1]; P. K. Roy[2]; [1]Lucent Technologies, Bell Laboratories, 600 Mountain Ave., Murray Hill, NJ 07974 USA; [2]Lucent Technologies , Bell Laboratories, 9333 S. John Young Parkway, Orlando, Fl 32819 USA

As the gate length of MOSFETs shrinks below 250nm, the thickness of SiO_2 gate oxides, if not replaced by an alternative high-k dielectric, must also decrease towards 4.0nm or even smaller. Tunneling behavior, long term stability and electrical reliability of such ultra-thin SiO_2 gate oxides are determined not only by the oxidation process, but to an increasing extent by the processing steps performed before and after oxide growth. We describe the effects of post-oxidation anneals on the structure and electrical characteristics of rapid thermally grown SiO_2 gate oxides with thicknesses between 1.5nm and 7.0nm. Using a set of physical and electrical measurements of the bare annealed and bare as-grown oxides as well as electrical measurements of PMOS- and NMOS-capacitor test structures, we obtain new insight into both oxide and interface properties. Infrared and X-ray measurements confirm the existence of a transition layer at the Si/SiO_2 interface of the RTO-oxides. The anneals smooth out this layer and reduce the total number of fixed charges. C-V and Quantox measurements confirm this trend. A comparison between 4.0nm as-grown gate oxides on p/p+ epi-substrate grown under atmospheric oxygen pressure and their annealed counterparts show a drop in N_{tot} from 7.88E11cm^{-2} to 2.19E11cm^{-2} for a 5 minute inert gas rapid thermal anneal and to 2.93E10cm^{-2} for a 60 minute inert gas furnace anneal. Moreover, Q_{bd} measurements show that post-oxidation anneals improve the breakdown reliability of the ultra-thin gate oxides. Charge to breakdown experiments on NMOS-capacitors with 4.0nm gate oxides grown in a 760torr oxygen environment reveal a reliability gain of about 2 for the annealed devices.

10:40 AM, F3

The Effect of Thin Gate Oxide with HF Vapor Pretreatment and In-Situ Native Oxide Desorption: ALBERT CHIN[1]; B. C. Lin[1]; W. J. Chen[2]; Y. B. Lin[3]; C. Tsai[1]; C. Tsai[1]; [1]National Chiao Tung University, Engineering Building 4, Hsinchu Taiwan; [2]National Yun-Lin Polytechnic Inst., Dept. of Mechanical Materials Eng., Huwei Taiwan; [3]Chung Hua Polytechnic Institute, Dept. of Electrical Engineering, Hsinchu Taiwan

It is reported recently by Bell Labs group at IEDM that an intrinsic defect may exist in thin gate oxide, and such defect will increase the leakage current that is similar to SILC. In this work, we have shown that this intrinsic defect can be improved by in-situ removing the native oxide followed by growing the high quality thermal oxide. Native oxide was removed by using HF vapor pretreatment and grown under a leak-tight low-pressure oxidation furnace. A low loading temperature and a high flow rate of hydrogen can avoid pre-matured oxidation by residual moisture and oxygen inside the reactor, after passivated H and F atoms are evaporated during furnace temperature ramped up. As observed by high resolutional TEM, interface roughness between oxide and Si is within 1 monolayer of Si atom for the 27 A oxide grown at 900 ℃. The achievement of such extremely sharp interface is attributed to native oxide desorption; it is believed that oxygen molecules will diffuse through the weak spot within the native oxide that will roughen the interface. Similar weak spot theory is also used to explain the shallow junction spiking. The measured I-V characteristic is comparable to those published in the literature. Good oxide reliability is also achieved, and no breakdown can be observed under a high current density stress of 11 A/cm^2 and a large charge injection of 7.9x10^4 coul/cm^2. Such high current density is used because there is no observable change at lower current densities after stress for two hours. However, the low-field gate-leakage current increases if there is a residual native oxide that roughens the interface. The increased interface roughness is also in consistent with the measured increase of hole-trap generation after stress. The measured voltage change after 7.9x10^4 coul/cm^2 stress is less than 0.1V for the oxide with the sharp interface. Therefore the reported intrinsic defect may be due to the effect of native oxide. By using such combined HF vapor pretreatment and in-situ clean, ultra-thin oxide of 11 A can be grown with atomically smooth interface and good electrical I-V and reliability characteristics.

11:00 AM, F4

Structural and Chemical Characterization of As-Deposited Microcrystalline Indium Oxide Films Prepared by DC Reactive Magnetron Sputtering: CHRISA XIIROUCHAKI[1]; Kostas Moschovis[2]; Elias Chatzitheodoridis[2]; George Kiriakidis[2]; Per Morgen[1]; [1]University of Odense, Physics Department, Campusvej 55, Odense M, Fyn DK-5230 Denmark; [2]University of Crete, IESL/FORTH, Physics Department, P.O. Box 1527, Heraklion, Crete GR-71110 Greece

Indium oxide (In_2O_3) is a very important material for microelectronic applications. It behaves as an insulator in its stoichiometric form and as a highly conducting semiconductor with a wide band gap (3-4 eV) in its non-stoichiometric form, providing high transparency in the visible light range and high reflectivity in the IR light range. This unique combination of electrical and optical properties makes this material obviously useful for applications in photovoltaic devices. The electrical conductivity in In_2O_3 arises from oxygen vacancies which act as donors of electrons to the conduction band. Indium oxide (InO_x) films with a thickness of 100-1600 nm were prepared by dc reactive magnetron sputtering

onto Corning glass 7059 substrates in various mixtures of oxygen in argon at room temperature. The as-deposited films were microcrystalline with a crystallite size of 20.6 nm as revealed by x-ray diffraction analysis. The microstructure of the films was investigated using electron diffraction and scanning transmission electron microscopy. For this purpose, films with a thickness of about 100 nm were deposited on NaCl substrates. The electron diffraction pattern of the films was that of a typical microcrystalline film with many small crystallites, while the TEM images showed that the films consist of morphologically homogeneous microcrystals. The stoichiometry and the electrical properties of these films can change under exposure to ultraviolet (UV) light in vacuum. It has been found that the conductivity can increase by about six orders of magnitude, between an insulating and a very conductive state, by exposing the film to UV light in vacuum, while by subsequently exposing the same film to an oxidizing atmosphere it reverts to the initial insulating state. The process of photoreduction and oxidation is fully reversible. The mechanism responsible for these large changes in conductivity is estimated to be the UV induced production of oxygen vacancies resulting in a degenerate electron gas in the conduction band. The surface and depth composition of the films were examined using Auger electron spectroscopy (AES) combined with depth profiling analysis. Quantitative Auger and energy dispersive x-ray (EDX) analysis were employed to determine the stoichiometry of the films. An oxygen deficiency of 2-5% was found in these films with respect to the stoichiometric composition. The effect of film thickness and oxygen content during the deposition on the stoichiometry were examined. Both AES and EDX analyses confirmed that the stoichiometry is invariant for these parameters. The depth profiling analysis showed that all films exhibit an extremely good in-depth uniformity, all way to the interface with the glass substrate, regardless of their thickness. To our knowledge, this is the first time that such depth profiles have been presented for relatively thick InO_x films.

11:20 AM, F5

Thin SOI Using Polish Stop Technology: DIANE GAY[1]; P T Baine[1]; H S Gamble[1]; B M Armstrong[1]; S J N Mitchell[1]; [1]Queens University Belfast, Electrical Electronic Engineering, Ashby Building, Stranmillis Road, Belfast, Co Antrim BT9 5AH Northern Ireland

Many techniques have been used to produce Silicon-On-Insulator (SOI), For thick SOI these include precision grinding and polishing, which is capable of producing SOI layer with a thickness of 2micron ±0.5micron. For thin, less than 1 mm, various etchstop technologies such as SIMOX, and epitaxial etchstop layers such as silicon germanium can be used. However, the quality of the resulting thin SOI can be compromised due to defects in the silicon layers. These defects can be caused by implantation or epitaxial growth. By using a polish stop technology, thin single crystal SOI can be achieved with excellent thickness uniformity. Materials such as silicon dioxide and silicon nitride have negligible polish rates when compared with silicon. These layers can also withstand the chemical etching process which occurs during polishing. This makes them ideal materials for a polish stop process. Standard 5micron SOI is readily obtainable by grinding and polishing. A polish stop process, with silicon nitride as a polish stop, can be achieved using the 5micron SOI as starting material. This paper describes such a process. Using standard masking and etching techniques, trenches can be formed in the 5micron SOI layer. These trenches can vary in width up to 6micron, and must be separated by a distance of up to 100micron. Silicon nitride is subsequently deposited, by Chemical Vapour Deposition, lining the trenched regions. The thickness of the deposited silicon nitride layer depends on the final silicon thickness required. The silicon nitride layer is patterned and etched leaving islands of silicon nitride only on the base of the trench. This forms the polish stop structure.. The trenched SOI structure undergoes Chemical Mechanical Polishing process(CMP). When the silicon nitride layer has been reached, polishing effectively stops, leaving a thin uniform SOI layer. Silicon layers as thin as 0.2micron can be achieved with uniformity ±0.05micron.

WEDNESDAY PM

June 24, 1998

Session G. Epitaxy for Devices

Room: E303
Location: Thornton Hall

Session Chairs: Ray Tsui, Motorola, Tempe, AZ 85284 USA; Dwight Streit, TRW

1:30 PM, G1

High DC Current Gain in $In_{0.48}(Al_xGa_{1-x})_{0.52}P$/GaAs HBTs : CHARLES R. LUTZ[1]; Noren Pan[1]; Roger E. Welser[1]; D.P. Vu[1]; [1]Kopin Corporation, 695 Myles Standish Blvd., Taunton, MA. 02780 USA

The Heterojunction Bipolar Transistor (HBT) is gaining wide favor as the device of choice for high frequency, high power microelectronic applications. The principal benefits of HBTs are realized through the devices ability to suppress the injection of holes from the base into the emitter region, a consequence of the large valence band discontinuity (ΔEv) at the base/emitter heterojunction. Typically, AlGaAs is used in the emitter layers of GaAs-based HBTs. However, in recent years InGaP with its larger valence band discontinuity has been receiving considerable attention. Inherent advantages of this material system including lower surface recombination velocities, high etch selectivity, and increased temperature stability are key factors to obtaining exceptionally reliable compact microwave devices which will be required for high power microwave and millimeter wave applications. The use of emitter materials which provide the largest possible valence band offsets is essential for obtaining optimized current gain performance in devices intended for high-frequency power and switching applications. The quaternary $In_{0.48}(Al_xGa_{1-x})_{0.52}P$ material system is a promising candidate as it possesses the largest energy bandgap of any of the III-V materials lattice-matched to GaAs, resulting in a ΔEv in the range of 0.27- 0.62 eV. The purpose of this paper is to compare the device characteristics of high performance AlInGaP/GaAs HBTs with state-of-the art AlGaAs/GaAs and GaInP/GaAs HBTs. The DC characteristics of large-area HBTs (75 microns x 75 microns emitter contact area) are used to assess the quality of critical epitaxial layers within the device. Initial results indicate that both InGaP/GaAs and AlInGaP/GaAs devices exhibit similar DC performance characteristics to those of recently reported AlGaAs/GaAs HBTs with similar base sheet resistances. Measured gains in excess of 125 \@ 1kA/cm^2 were obtained for an $In_{0.48}(Al_xGa_{1-x})_{0.52}P$ (x=0.18) emitter HBT with a base thickness of 800 Å and carbon-doped to a level of 4E19 cm^{-3} (base sheet resistance of 230 Ω/sq.). We believe that this is the highest DC current gain ever observed at this low base sheet resistance for this material system. A useful figure of merit to determine the quality of HBTs is the gain/base sheet ratio, which in this case is as high as 0.55. In general, a gain/base sheet ratio greater than 0.5 is indicative of very high quality material. Photoluminescence and photoreflectance characterization of these HBTs will be correlated to the large area electrical properties of the device. The impact on the RF device performance and long-term reliability will also be discussed.

1:50 PM, G2

MBE Growth of AlInAs/GaInAs Lattice Relaxed Layers for HEMT Aapplication on GaAs Substrate: Y. CORDIER[1]; M. Zaknoune[1]; S. Bollaert[1]; J. Dipersio[2]; D. Ferre[2]; [1]Institut d'Electronique et de Microelectronique du Nord, Universite de Lille 1, Avenue Poincare, BP 69, 59652, Villeneuve d'Ascq Cedex, France; [2]LSPES, Universite de Lille 1, URA 234, France

The development of lattice mismatched AlInAs/GaInAs High Electron Mobility Transistors on high-quality GaAs substrates (metamorphic HEMT) is of primary interest for millimeter-wave devices, allowing an arbitrary choice of Indium content at the heterojunction. Buffer layers with composition grades have been proposed to obtain strain relaxation and efficient misfit dislocation filtering within either GaInAs, AlInAs or GaAlInAs material. Continuously graded buffer

layers are preferred to step graded ones since they do not exhibit critical strain at interfaces and the feasibility of insulating InAlAs metamorphic buffer layers has been demonstrated in a previous work. The aim of this work was to study MBE growth of lattice relaxed AlInAs/GaInAs layers for HEMT application. In particular, we investigated the "low Indium content" range (from 30% to 42% Indium content) which presents two interesting features : (I) it provides higher band gap discontinuity at the heterojunction, (II) the lattice mismatch is lower compared to InP related materials (Indium content close to 53%). In a first step, the influence of the shape of the grade (sublinear and linear) and its thickness has been investigated in different structures as follows: simple grades, grades ended by a constant composition step, and grades ended by lower composition step (inverse step). In a second step, lattice relaxed HEMT epilayers were grown. Strain relaxation as well as surface morphology have been studied with high resolution X-ray diffraction and atomic force microscopy respectively, showing the interest of using inverse step layers to achieve higher relaxation of mismatch strain. Both structural and electrical measurements attest the quality of the layers. Atomic force microscopy exhibit mean roughness from 1 nm for lower Indium content epilayers (x_{In}=30%) to 4 nm for 50% Indium content ones and relaxation rates close to 98% have been measured. On the other hand Hall effect measurements clearly show an improvement of electron mobility in the GaInAs channel when the Indium content is increased. Moreover, for low Indium content layers (x_{In}=30%-35%), sheet carrier density and mobility into the channel is very sensitive to the delta doping of InAlAs barrier layer as well as the Indium content. Nevertheless $Al_{0.68}In_{0.32}As/Ga_{0.67}In_{0.33}As$ heterojunction doped with 10^{13} at. Si/cm^{-2} produced Ns_{300K}=3.4x10^{12} cm^{-2} (Ns_{77K}=3.46x10^{12} cm^{-2}) with high electron mobility μ300K=8250 cm^2/Vs (μ77K=23400 cm^2/Vs) and high performance 0.1 μm gate length transistors with current gain cut-off frequency up to 160 GHz have been realized.

2:10 PM, G3

MOVPE Growth of GaSbP on InP for HEMT Applications: DANIEL DOCTOR[1]; Mehran Matloubian[1]; Chanh Nguyen[1]; Steven Bui[1]; Catherine Ngo[1]; [1]HRL Laboratories, MS RL61a, 3011 Malibu Canyon Rd., Malibu, CA 90265-4799 USA

In this paper we report on the MQVPE growth of GaPSb compounds on InP substrates for HEMT applications. The PSB materials system offers the potential for much higher performance with its use in HEMT device structures grown on InP substrates. The use of GaPSb (AlPSb) to replace the InAlAs, typically used in HEMTs grown on InP substrates, as the Schottky barrier layer provides an estimated O.85cV (1.07eV) conduction band discontinuity to an InGaAs channel layer. The large conduction band discontinuity greatly increase carrier confinement, maximum current capacity, and transconductance leading to much improved HEMT device performance [1]. However growth of the PSb materials is very difficult. Due to the large difference in lattice constant between the end binary compounds, GaPSb has a miscibility gap that extends over nearly the entire composition range at normal growth temperatures. Only non-equilibrium growth techniques like MOVPE and MBE can be used to grow the compounds. In addition, the alloy composition of GaPSb is extremely sensitive to both the P/Sb ratio and the growth temperature, which changes the reactivity of the group V elements on the surface. We will show xray data from different bulk layers of GaPSb grown near lattice match of InP in our laboratory. We observe sharp xray peaks, which indicate high quality GaPSb film growth, and we demonstrate control of the alloy composition by varying group V flows and growth temperature. We also report on the n-type dopant behavior of Si and Sn in GaPSb. Both Si and Sn can effectively dope GaPSb layers grown lattice matched to InP. Our data suggests that the donor activation energies may range from 50-100meV. We will also present material characterization results for a new GaPSb/InGaAsHEMT on InP device structure, using the GaPSb as the Schottky barrier layer. We have achieved excellent device material qualities. From Hall measurements for several GaPSb/InGaAs HEMT devices with different dopant flows we have achieved sheet charge densities from 2.2-3.8E12cm^{-2} with Hall mobilities near l0,000cm^{2}Vs. We will report on the details of the GaPSb growth and the materials characterization of the bulk layers of GaPSb and the GaPSb/InGaAs HEMT structures. We have used RTPL and LTPL. Hall, SIMS, and xray diffraction measurements to characterize the growth structures. [1] C. Nguyen, T. Liu, and M. Matloubian, "High-speed, Low-noise millimeter wavbe HEMT and pseudomorphic Æ U.S. Patent No. 5,548,140, August 20, 1996.

2:30 PM, G4

Molecular Beam Epitaxy for InAs/AlSb High Electron Mobility Transistors: B. R. BENNETT[1]; J. B. Boos[1]; B. V. Shanabrook[1]; M. J. Yang[1]; R. MAGNO[1]; D. Park[1]; W. Kruppa[1]; M. E. TWIGG[1]; [1]Naval Research Laboratory, Electronics Science and Technology Division, Code 6876, 4555 Overlook Avenue, SW, Washington, DC 20375-5347 USA

Single quantum wells of InAs clad by AlSb are of interest for applications that require low-voltage, high-speed field-effect transistors. Advantages of this material system include the high electron mobility (30 000 cm^2/V-s) and peak velocity (4 x 10^7 cm/s) of InAs, and a large conduction band offset between InAs and AlSb (1.35 eV). Obstacles have included the lack of a suitable n-type dopant for AlSb, and relatively large leakage currents in high electron mobility transistors (HEMTs). In this talk, we will demonstrate the use of InAs(Si) modulation doping to achieve higher sheet carrier concentrations, and the insertion of a mismatched InAlAs layer to reduce leakage currents and enable a gate-recess etch prior to the gate metal definition. Sheet carrier concentrations in quantum wells of InAs clad by AlSb were enhanced by modulation doping with very thin (9-12 Å) remote InAs(Si) donor layers. The large confinement energy in the donor layer allows the transfer of electrons to the 150 Å undoped InAs channel. The growth temperature of the donor layers was a key parameter, with relatively low temperatures required to minimize Si segregation into the AlSb. Sheet carrier concentrations as high as 3.2 x 10^{12}/cm^2 and 5.6 x 10^{12}/cm^2 were achieved by single- and double-sided modulation doping, respectively. HEMTs fabricated using the modulation-doped structure exhibited a current gain cut-off frequency, f_T, of 45 GHz for a 0.5 um gate length at a source-drain voltage of 0.4 V. Although electrons are confined in an InAs/AlSb quantum well by the large conduction band offset, the valence band offset is too small for adequate confinement of the holes. These holes are thought to contribute to HEMT leakage currents. To provide a barrier for hole transport, we included a 40 Å layer of $In_{0.4}Al_{0.6}As$ between the AlSb barrier and the InAs cap. The lattice constant of $In_{0.4}Al_{0.6}As$ is 5% smaller than that of AlSb. Despite this large mismatch, TEM reveals a continuous film, and AFM measurements show an rms roughness of only 3-6 Å. The electron mobilities remain high (17 000-29 000 cm^2/V-s at 300K) for heterostructures including the InAlAs layers. HEMTs with a 0.1 um gate length exhibit a transconductance of 600 mS/mm and an f_T of 120 GHz at a source-drain voltage of 0.6 V.

2:50 PM, G5

Composite-Channel InP-InGaAs HEMT Material for Optimized Millimeter Wave Power Performance: YAOCHUNG CHEN[1]; April S. Brown[2]; Tongho Kim[2]; Robert A. Metzger[2]; Richard Lai[1]; Yeong-Chang Chou[1]; Huan-Chun Yen[1]; Dwight C. Streit[1]; [1]TRW, Inc., Electronics & Technology Division, One Space Park, Redondo Beach, CA 90278 USA; [2]Georgia Institute of Technology, School of Electrical and Computer Engineering, Atlanta, Georgia 30332 USA

We have correlated epitaxial material design, material characterization results, and device results of composite-channel stepped quantum-well InP-InGaAs power HEMTs. We have established a correlation between material design and device results to achieve improved power performance at millimeter wave frequencies above 60 GHz. The composite channel InP-InGaAs HEMT structures were grown by solid-source phosphorus MBE. Epitaxial material design variations included InP channel thickness, the InGaAs quantum well thickness, sheet charge density and charge distribution on either side of the stepped quantum well, buffer layer design, and Schottky-barrier hole-blocking layer design. High power 0.15 μm gate-length power HEMTs fabricated using the best of these epitaxial material designs have demonstrated the optimum combination of improved device breakdown voltage and excellent high frequency performance. The epitaxial material and device correlations are summarized as follows. (1) An InP second channel of 30 nm results in optimized mobility. Reducing the InP layer thickness below 30 nm degrades the channel mobility. (2) An InGaAs channel of 20 nm yields optimized current density. The maximum channel current scales with InGaAs channel thickness up to 20 nm. (3) Electron mobility >10,000 cm^2/Vs is achieved with channel carrier density of 4x10^{12} cm^{-2}. Sheet charge above this concentration yields degraded channel mobility. (4) A Schottky barrier layer consisting of $In_{0.4}Al_{0.6}As$ and InGaP is effective as a hole blocking layer but degrades the ohmic contact resistance and complicates the gate recess process. The best Schottky-diode contact layer uses pseudomorphic $In_{0.4}Al_{0.6}As$ for control of hole injection, resulting in reduced gate leakage current and improved breakdown. An 8-fingered 0.15 mm T-gate composite channel HEMT power amplifier using our optimized profile and gate recess process demonstrated a maximum channel current of 600 mA/mm and a maximum transconductance of 900 mS/mm with on state breakdown greater

than 4.5V at a current density of 830 mA/mm, corresponding to a DC power density of 3.6 W/mm. The composite-channel InP-InGaAs HEMT has better drain bias capability than our baseline InGaAs-InAlAs, which has achieved 200 mW output power at 94 GHz.

3:10 PM Break

3:30 PM, G6

Bandgap Engineered Optical Interconnects Using Selective Area Growth Metalorganic Chemical Vapor Deposition: MUHAMMAD ASHRAFUL ALAM[1]; ROOSEVELT PEOPLE[1]; J. Johnson[1]; S. Sputz[1]; David Lang[1]; Eric Issacs[1]; Ken Evan-Lutterodt[1]; Mark Hybertsen[1]; J Vandenberg[1]; [1]Bell Laboratory, Lucent Technology, 600 Mountain Avenue, Murray Hill, NJ 07974 USA

The use of optical components in modern telecommunication system has been steadily increasing over the last several years. As the bit rate and the transmission distance increases, so does the need for lower loss, smaller cost, and compact subsystems that have fewer alignment points. Since photonic integrated circuits can effectively address these issues, there have been many different proposals to achieve good interconnects among photonic devices. One particularly novel technique involves the use of selective area MOCVD growth using oxide masks to form the optical interconnects [1]. In this presentation, we shall discuss a computational model for selective area MOCVD growth called the vapor phase diffusion (VPD) model. In this vapor phase transport model, one assumes the existence of a stagnant layer of carrier gas (i.e. H2) in contact with the wafer. The growth precursors diffuse through this stagnant layer to react on the substrate. In the selective area growth process, this reaction is spatially modulated by placing dielectricoxide pads on the wafer. The pads inhibit local growth and modify the diffusion pattern of the reacting gases within the stagnant layer. This leads to compositional variation of the deposited films adjacent to the dielectric pads. By appropriate design of the oxide pads, one can precisely engineer a film of predefined thickness, bandgap, and strain variation. Films of such controlled dimensions and composition have wide ranging applications as optical interconnects in Electro-Absorption Modulator (EML), expanded beam lasers and amplifiers, etc. A two-dimensional version of the VPD model has been introduced by Thrush et al. [2] and later by Jones et al. [3]. This 2D model applies to infinitely long dielectric pads with uniform cross section. However, for longitudinal bandgap engineering as is required for optical interconnects, the oxide pads must be finite in both dimensions requiring the solution of the diffusion model in three dimensions. In this presentation, the results from the 3D diffusion model will be thoroughly analyzed for different pad geometries and reactor pressures. Moreover, we shall verify the model with extensive characterization of the grown profiles using atomic-force microscopy and optical interference microscopy to determine thickness variation, spatially resolved micro-photoluminescence to determine bandgap, and micro-Xray diffraction to determine local strain. A design example will be given and key physics issues, including the assumptions behind the computational model, will be discussed. References———————1. T. Sasaki, M. Yamaguchi, K. Komatsu, and I. Mito,IEICE Trans. Electron, vol. E80-C, No. 5, p. 654, (1997). 2. E.J. Thrush, J.P. Stagg, M.A.Gibbon, R.E. Mallard, B. Hamilton,J.W. Jowett, and E.M. Allen, Materials Science and Engineering, B21, p. 130 (1993). 3. A.M.Jones, M.L. Osowski, R.M. Lammert, J.A. Dantzig, andJ.J. Coleman, J. of Electron. Materials, vol. 24, p. 1631 (1995).

3:50 PM, G7+

Thin Multiplication-Region InAlAs Homojunction Avalanche Photodiodes Grown On InP By MBE: CHET LENOX[1]; Hui Nie[1]; Ping Yuan[1]; Geoff Kinsey[1]; Joe Campbell[1]; Chad Hansing[1]; Archie Holmes[1]; Ben Streetman[1]; [1]University of Texas at Austin, Microelectronics Research Center, PRC/MER R9900, Austin, TX 78712-1080 USA

Avalanche photodiodes (APDs) are often used in optical communication systems due to their increased sensitivity as compared to conventional p-i-n photodetectors. The impact ionization process that provides this enhanced sensitivity also places a limit on the high-frequency performance of the device due to increased avalanche build-up times at high gains. Low overall device noise is also desirable to improve the signal-to-noise characteristics of the photodetector. Both these factors necessitate the use of a multiplication region exhibiting low excess noise due to the avalanche process. $In_{0.53}Ga_{0.47}As$ grown lattice-matched to InP substrates is often used as an absorption region in APDs due to its compatibility with the wavelengths required for fiber-optic detection (1.3 and 1.5μm). Unfortunately, the wide-bandgap compound semiconductors grown lattice matched to this material (InP, InGaAsP, and InAlGaAs) that would provide a suitable multiplication region have similar electron and hole ionization rates, resulting in a symmetric multiplication process with high excess noise and long build-up times. A number of design techniques have been utilized to improve the noise characteristics and frequency performance of multiplication regions in APDs. Multiple-quantum-well (MQW) APDs have been shown to improve device performance, purportedly due to enhanced electron versus hole ionization rates resulting from conduction band discontinuities. [1][2] More recently, APDs utilizing very thin AlGaAs multiplication regions (50-1000 nm) have resulted in very low measured excess noise [3][4] and excellent high-frequency performance [5]. We present here the gain and noise characteristics of InAlAs homojunction APDs grown on InP by MBE. To study the avalanche characteristics of thin regions in this material, a series of p-i-n APDs were fabricated with multiplication region widths ranging from 100 to 1600nm. As was seen in AlGaAs devices, decreased excess noise was measured for thinner multiplication region widths. Low dark currents of <2nA were measured at 90% of breakdown for 175mm diameter mesa-isolated devices. A maximum gain of over 100 has been measured on a number of devices. Thus, our results indicate that InAlAs should provide an excellent multiplication material in separate absorption and multiplication (SAM) APDs designed to detect at 1.55μm. Comparison with previously published InAlAs ionization data in conventional thick-multiplication regions and techniques for achieving high quality MBE growth in this material system will also be presented. This includes the use of lattice-matched InGaAs buffer layers and the pre-growth removal of InP surface oxides under either arsenic or phosphorous flux. [1] T. Kagawa, Y. Kawamura, H. Iwamura, IEEE Journal of Quantum Electronics, vol. 29, pp. 1387-392, 1993. [2] K. Makita, I. Watanabe, M. Tsuji, K. Taguchi, Proc. IOOC-95, TuB 2-1, 1995. [3] K.A. Anselm, P. Yuan, C. Hu, C. Lenox, H. Nie, G. Kinsey, J.C. Campbell, B.G. Streetman, Applied Physics Letters, vol. 71, pp. 3883-3885, 1997. [4] K.F. Li, D.S. Ong, J.P.R. David, P.N. Robson, R.C. Tozer, G.J. Rees, R. Grey, presented at 55th IEEE Device Research Conference, Colorado, June 1997. [5] H. Nie, K.A. Anselm, C. Lenox, P. Yuan, C. Hu, G. Kinsey, B.G. Streetman, J.C. Campbell, submitted Photonics Technology Letters, 1997.

4:10 PM, G8

Fabrication of Surface Tunneling Transistors by A Self-Align Process Using A Regrowth Technique: YONG-JIN CHUN[1]; Tetsuya Uemura[1]; Toshio Baba[1]; [1]NEC Corporation, Fundamental Research Laboratories , 34 Miyukigaoka, Tsukuba, Ibaraki 305-8501 Japan

We have proposed a surface tunneling transistor (STT), in which an interband tunnel junction is formed under a gate between a source and a drain, as a future functional device in high speed and low-power circuits and demonstrated successful transistor operations using GaAs or InGaAs material systems [1, 2]. In the STT fabrication process using a drain mesa structure, however, a large gate-drain overlap region is formed. Due to the existence of this region, the miniaturization of STT is limited. In this study, a self-align process, where the source/drain region was formed by using a regrowth technique after the gate-region formation, was investigated so that the miniaturization and integration of STTs could be improved. Layers consisting of 500-nm-thick AlInAs, 50-nm-thick InGaAs, 12-nm-thick n^+-InGaAs (Si = $8x10^{18}$ cm^{-3}), 10-nm-thick InGaAs, 50-nm-thick AlInAs, and 10-nm-thick p^+-InGaAs (Be = $8x10^{19}$ cm^{-3}) were grown on semi-insulated InP substrates at 460℃ by using molecular beam epitaxy (MBE). The gate region was formed by chemical etching. In this process, we found that the carbon contamination of the etched surface was significantly suppressed when a double mask structure of SiN_x/SiO_2 was used. Moreover, the surface morphology of a regrown p^+-InGaAs layer was better than that obtained with the use of a photoresist mask. We also investigated the effect of the growth temperature on the surface morphology. At the growth temperature of 460℃, the RHEED pattern was changing from streak to spot during the growth and the rough surface was formed. On the other hand, the streak pattern was maintained during growth and a flat regrown surface was obtained at the lower growth temperature of 400℃. These results indicate that low-temperature growth as well as a double mask structure is very effective in obtaining a flat regrown surface. By using this process, we fabricated the self-aligned InGaAs-based STTs. There is no gate-drain overlap region in the fabricated STTs. The gate-controlled negative differential resistance (NDR) characteristics with a peak-to-valley (P/V) ratio of 2.5 were clearly observed in the positive and negative drain voltages. This successful transistor operation indicates that this self-align process is very useful for the miniaturization and integration of STTs. This work was performed under the management of FED as a part of the MITI R&D Program (Quantum Functional Devices Project) supported by NEDO. [1] T.

Uemura and T. Baba: Jpn. J. Appl. Phys. 33 (1994) L1363. [2] T. Uemura and T. Baba: IEEE Electron Device Lett. 18 (1997) 225.

4:30 PM, G9

Negative Differential Resistance of CdF_2/CaF_2 Resonant Tunneling Diode on Si(111) Grown by Partially Ionized Beam Epitaxy: MASAHIRO WATANABE[1]; Yuichi Aoki[1]; Wataru Saitoh[2]; Mika Tsuganezawa[1]; [1]Tokyo Institute of Technology, Research Center for Quantum Effect Electronics, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552 Japan; [2]Tokyo Institute of Technology, Electrical and Electronic Engineering, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552 Japan

Epitaxial growth of nanometer-thick CdF_2/CaF_2 multilayered heterostructures on a Si(111) substrate using partially ionized beam epitaxy has been demonstrated. Triple barrier resonant tunneling diode (RTD) consisting of these heterostructures were fabricated on Si and negative differential resistance (NDR) characteristics have been observed at room temperature. CdF_2/CaF_2 heterostructure is one of the attractive candidates for quantum effect devices on Si substrate such as resonant tunneling diodes and quantum cascade lasers because of its large conduction band discontinuity (2.9eV) at the heterointerface. CdF_2 and CaF_2 have fluorite lattice structure and well lattice matched to Si with mismatches of -0.8%, +0.6% at room temperature, respectively. Recently, epitaxial growth of CdF_2/CaF_2 heterostructure on Si(111) using molecular beam epitaxy (MBE) has been reported and room temperature NDR with double barrier RTD has been demonstrated by A. Izumi et al. In this paper, we have introduced partially ionized beam epitaxy (PIBE) for obtaining atomically flat CdF_2-CaF_2 heterointerface using ionization and acceleration of CaF_2. N-type Si(111) substrate with 0.1° misorientation was chemically cleaned and protective oxide layer was removed in ultra high vacuum chamber by thermal heating with Si flux. First of all, 1nm-thick CaF_2 was grown at 750°C, with ionization by electron bombardment without acceleration bias voltage (V_a). Ionization of CaF_2 was effective for improvement of CaF_2 flatness and coverage over Si surface probably because ionized CaF_2 tends to make strong bonding with Si. Subsequently, 5nm-thick CdF_2 buffer layer was grown on the CaF_2 at 50°C. After the buffer layer growth, CaF_2 was grown at 50°C with ionization and acceleration V_a=2kV and CdF_2 was grown at 50°C without ionization. The structure of triple barrier RTD is as follows: Al electrode (electron injector)/1nm-thick CaF_2 barrier/ 2nm-thick CdF_2 quantum well/ 1nm-CaF_2 / 1nm-CdF_2/ 1nm-CaF_2 / 5nm-thick CdF_2 buffer layer/ 1nm-thick CaF_2 buffer layer/ n-type Si(111) substrate/ Al electrode. Diameter of the top Al contact was 0.018mm. In the measurement of current-voltage characteristics, clear NDR was observed at room temperature and the maximum peak to valley (P/V) ratio was about 14. The NDR characteristic was almost reproduced three times and the bias voltage of peak current was 1.5V, which agreed well with theoretical estimation. The peak current density was 70-95A/cm^2, which is approximately 10 times lower than theory probably because the resonant tunneling occurred in a part of the whole contact area of devices due to the barrier thickness fluctuation. References:[1]A. Izumi, N. Matsubara, Y. Kushida, K. Tsutsui, and N. S. Sokolov: Jpn. J. Appl. Phys., 36 (1997) 1849. [2]M. Watanabe, W. Saitoh, Y. Aoki, J. Nishiyama: Solid State Electronics, to be published.

4:50 PM, G10
Late News

Wednesday PM, June 24, 1998

Session H. Growth and Characterization of SiGe and SiGeC Heterostructures

Room: 005
Location: Olsson Hall

Session Chair: Julia Hsu, University of Virginia

1:30 PM, H1+

Luminescence Analysis of Germanium Nanostructures Grown on SiGe/Si (118) by MBE: MURIELLE SERPENTINI[1]; Georges Bremond[1]; Abdel Kader Souifi[1]; Mario Abdallah[2]; Isabelle Berbezier[2]; [1]INSA Lyon, Laboratoire de Physique de la matière, UMR-CNRS 5511, bâtiment 502, 20 Avenue A.Einstein, Villeurbanne, Rhône 69621 France; [2]Campus de Luminy, CRMC2-CNRS, CASE 913, Marseille, Bouches du Rhone 13288 France

Quantum dots are expected to increase quantum efficiency and therefore are good candidates for the development of Si-based Optoelectronics. With this aim in view, self-organization growth on silicon (118) substrate seems to be a promising technique. The principle is as follows: a SiGe undulating layer is obtained by the growth on a silicon (118) substrate, then Ge is deposed on these undulations according to the Stranski-Krastanov mode. Using this method, the island lateral size can be better controlled. In this work we describe a photoluminescence investigation of such Si/Ge/SiGe/Si structures. We dispose of three samples with variable Ge thickness D (1, 3 and 7 monolayers) and one sample containing 7 monolayers of Ge without the first SiGe wetting layer. The study consists of time-resolved measurements and analyses of the photoluminescence signal as function of power excitation and temperature. Low temperature PL spectra show the 2D/3D changeover in the growth mode which occurs between D = 3ML and D = 7 ML. When increasing the temperature up to 300 K, the dots-related luminescence persists for the sample with D = 7 ML. For D = 3 ML, we observe a luminescence correlated to thickness oscillations. When increasing the power excitation, results show a shift of the picks towards higher energies. This shift is very significant for D = 7 ML, so we assume that the 3D-related transition is a type II optical transition. Time-resolved measurements are used in order to discuss the PL life-time of 2D and 3D related-transitions. This allows to separate the different contributions arising from different regions of the structures.

1:50 PM, H2+

Mechanisms Determining Three-dimensional SiGe Islands Density on Si(001): J. S. SULLIVAN[1]; H. Evans[1]; M. R. Wilson[1]; T. F. Kuech[2]; M. G. Lagally[1]; [1]University of Wisconsin - Madison, Materials Science Department, 1500 Engineering Drive, Madison, WI 53706 USA; [2]University of Wisconsin - Madison, Department of Chemical Engineering, 1415 Engineering Drive, Madison, WI 53706 USA

Thin, epitaxial films of SiGe deposited on Si(001) can form three-dimensional (3-D), coherently strained islands via a modified Stranski-Krastanov growth mode. Scientific interest in such islands has shifted from their novelty to mechanisms of growth and of formation. Additionally, engineering films with specific island sizes and densities may be of practical value for unique optoelectronic properties. This paper describes the mechanisms affected by common process variables in epitaxial growth and how these mechanisms determine film morphology. We deposited SiGe films on Si(001) using low-pressure chemical vapor deposition in an ultra-high vacuum compatible reactor. Alloy composition, substrate temperature, and deposition rate were used to control the number density of faceted 3-D islands. Film growth was monitored with in-situ, real-time reflection high-energy electron diffraction, and the growth was quenched when the diffraction patterns displayed transmission spots and angled streaks indicating the presence of 3-D faceted islands. Atomic force microscopy was performed ex-situ to characterize film morphology. Island number density exhibits an Arrhenius-type dependence with substrate temperature. The density increases approximately a factor of two for every 50 K decrease in temperature (near 1000 K). Two thermally activated processes can account for increased island density with decreasing temperature, diffusion length and diffusion barriers. If the distance between two islands is greater than the diffusion length, another island is likely to nucleate between them. Diffusion barriers increase the two-dimensional (2-D) adatom gas density reducing the effective diffusion length at a given temperature. Three-dimensional island density increases as a power law with deposition rate. Increasing the deposition rate increases the 2-D adatom gas density. The higher 2-D adatom gas density leads to an effectively shorter diffusion length allowing 3-D islands to nucleate closer together. Number density is inversely proportional to Ge mole fraction in the alloy. Islands may "sense" the presence of other islands by strain fields that propagate through the substrate. A compressively strained coherent island will impart a compressive stress on the surrounding substrate which diminishes with distance from the island. The local chemical potential for the alloy near an island will increase due to the compressively strained substrate. The increased chemical potential prevents islands from being too close. Furthermore, alloy composition affects the magnitude of the strain fields such that higher Ge mole fractions increase the

radius around an island where nucleation of another island is unfavorable. The process variables of alloy composition, substrate temperature, and growth rate influence 3-D island density through various mechanisms. We will discuss our results in the context of simple thermodynamic and kinetic models that may be used to engineer films with a desired 3-D island density. This work was supported by the NSF.

2:10 PM, H3+

Facet Formations in Selective Epitaxial Growth of SiGe/Si Heterostructures Grown By Gas-Source Molecular Beam Epitaxy: GREG D. U'REN[1]; Mark S. Goorsky[1]; Kang L. Wang[2]; [1]UCLA, Dept. of Materials Science & Eng., 420 Westwood Plaza, 6532 Boelter Hall, LA, CA 90095-1595 USA; [2]UCLA, Dept. of Electrical Engineering, 420 Westwood Plaza, Room 66-147, Engineering IV, LA, CA 90095-1594 USA

Gas-source molecular beam epitaxy was used to investigate facet formations occurring in the selective epitaxial growth of $Si_{1-x}Ge_xSi$ heterostructures ($x < 0.2$). We carried out experiments on nominal on-axis (100) Si substrates masked with 500-600 Å thermally grown SiO_2. Arrays 5 x 5 mm^2 of rectangular features 1-25 μm were defined by conventional photolithography techniques. Cross section transmission electron microscopy shows the development of {311} and {111} facets for a sidewall orientation parallel to the <110> directions. As growth proceeds and more importantly before lateral overgrowth, the {311} dominates. The combination of {111} and {311} facet growth leads to an overall lateral reduction of the (100) mesa top at an estimated rate of 2.2:1 [lateral reduction (x,y):epi thickness (z)]. The {311} facet grows approximately 3-4 times faster than the {111} facet, more quickly promoting the lateral reduction. With an appropriate Si buffer layer, the lateral dimension can be reduced beyond the original lithographic definition, which can be then used as a template for growth of SiGe heterostructures. Triple axis x-ray diffraction measurements of the selective epi determined that the crystalline quality is not compromised by the presence of facet growth nor subject to detectable additional strain relaxation mechanisms as a result of additional free surfaces for ⊕ 1 μm structures. Also, from double axis x-ray measurements, no significant growth dependence as function of feature size was observed. The extent of reduction is determined by the oxide thickness. Lateral reduction continues until the epi thickness overcomes the oxide, at which point overgrowth occurs. For epitaxial overgrowth of SiGe, the {111} facet becomes dominant consuming the {311} facet. The results for lateral overgrowth of SiGe are consistent with overgrowth of Si.

2:30 PM, H4+

Complete Suppression of Oxidation Enhancement of Boron Diffusion Using Substitutional Carbon Incorporation: M. S. CARROLL[1]; C. L. Chang[1]; J. C. Sturm[1]; T. Buyuklimanli[2]; [1]Princeton University, Department of Electrical Engineering, Center for Photonics and Optoelectronic Materials, Princeton, NJ 08540 USA; [2]Evans East, Plainsboro, NJ 08536 USA

Boron diffusion and its enhancement via implant damage (transient enhanced diffusion, TED) and oxidation (oxidation enhanced diffusion, OED) are severe problems for the scaling of Si based devices. Recently, the suppression of boron diffusion and the reduction of its enhancement due to OED and TED mechanisms has been demonstrated through the incorporation of carbon in siliconll,2]. In this paper we show for the first time the ability, through introduction of a thin SiGeC layer, to completely filter interstitials injected by an overlying oxidizing surface, which results in the complete elimination of OED for underlying boron. Further, we also quantify the ability of the SiCeC to reduce normal thermal diffusion and OED in Si layers lying above the SiGeC layer. The test structures were grown using rapid thermal chemical vapor deposition (RTCVD), between 600 and 750ϒC using methysilane as the carbon source. A double peaked boron profile with and without a SiGeC or SiGe layer placed between the peaks was used to test the effect of the layer on boron diffusivities at different locations (above and below) with respect to the SiGe/SiGeC layer. Both boron peaks were approximately 250A thick and had a boron concentration of $5*10^{19}/cm^3$ centered 2000A and 3000A away from the surface respectively, while the 250A thick SiGeC layer was centered 2300A from the surface. As-grown samples were then cleaved and annealed in nitrogen and oxygen ambient atmospheres at 850ϒC for 30 minutes. Boron profiles were characterized using secondary ion mass spectroscopy (SIMS), and a commercially available process simulator (TSUPREM4 by TMA) was used to quantitatively compare boron profiles and obtain boron diffusivities. Silicon samples, oxidation at 850ϒC is observed to cause a 10 times enhancement of boron diffusivity, consistent with existing simulators. Unlike previous reports of partial OED suppressions, introduction of 0.5% substitutional carbon in SiGeC between the oxidizing surface and boron marker completely suppresses any oxidation enhanced diffusion, presumably by filtering out all interstitials injected at the surface by the oxidation process. Work is in progress to determine the critical density of susbtitutional carbon to suppress boron OED. A comparison of Si, SiGe, and SiGeC samples shows that substitutional carbon, not Ge, is critical for this result. Further, we report a boron diffusivity 33% of that in the annealed Si control sample layer -350A above the SiGeC layer (i.e. between the top surface and the SiGeC layer). This nonlocal suppression of boron diffusion, indicates that the SiGeC getters Si interstitials with an effective range of over ~350A in all cases including annealing in oxygen atmospheres. This work was supported by ONR (NO0014-96-1-0334), and AFOSR. References:1. L. D. Lanzerotti, et. al, Appl. Phys. Lett. vol 70, No 23, 9 June 972. Stolk, H. J. Gossmann, D. J. Eaglesham, J. M. Pate, Mat. Sci. & Eng. B36, 275-81, 96

2:50 PM, H5+

Effect of Low Carbon Levels on Boron Diffusion and Strain Relaxation in $Si_{1-y}C_y$ and $Si_{1-x-y}Ge_xC_y$ Alloys: ANDA C. MOCUTA[1]; Richard Strong[2]; David W Greve[1]; [1]Carnegie Mellon University, Department of Electrical and Computer Engineering, 5000 Forbes Ave. , Pittsburgh, PA 15213 USA; [2]Northrop Grumman, STC, 1350 Beulah Rd., Pittsburgh, PA 15235 USA

We report the growth of p-type $Si_{1-y}C_y$ and $Si_{1-x-y}Ge_xC_y$ epitaxial layers using Ultra High Vacuum Chemical Vapor Deposition (UHV/CVD). This is a novel application of UHV/CVD, a batch process epitaxial growth technique used in the commercial manufacture of Si-based integrated circuits. Silane, germane, and methylsilane were used as the source gases for Si, Ge, and C respectively. Boron doping was achieved both by (1) in-situ doping using diborane; and (2) B-implantation followed by annealing. Both doped and undoped layers were annealed at temperatures of up to 900 °C and analyzed using SIMS and high-resolution X-ray diffraction. For small concentrations (0.25%), carbon incorporation is completely substitutional in both $Si_{1-y}C_y$ and $Si_{1-x-y}Ge_xC_y$. These low carbon levels produce a significant enhancement in the thermal stability of SiGe alloys. Upon annealing at 900 °C for 1 hour, no significant strain relaxation occurs in SiGeC single layers or multiple quantum well structures while in similar SiGe structures with comparable strain and thickness strain relaxation is observed. The addition of carbon also greatly reduces the diffusivity of boron, regardless of whether the boron is implanted or incorporated during growth. For a 900 °C, 30 min anneal boron diffusion has been effectively inhibited in $Si_{1-y}C_y$ and a reduction in diffusion coefficient by at least a factor of 10 could be calculated. Sheet resistances of $Si_{1-y}C_y$ films with [B] ~ 10^{19} cm^{-3} are unaffected by low carbon levels; I/V characteristics of pn junctions show no increase in recombination current with the addition of 0.25% carbon. Fabrication of SiGe heterojunction bipolar transistors or p-channel MOSFETs involves both ion implantation and high temperature annealing steps. These results demonstrate that incorporating small amounts of substitutional carbon into films grown by UHV/CVD can have beneficial effects in processing devices by allowing a higher thermal budget.

3:10 PM Break

3:30 PM, H6

Effect of Growth Interruption on Si/SiGe Layers Using UHVCVD: JACK O. CHU[1]; Khaled Ismail[1]; Steve Koester[1]; [1]IBM T.J. Watson Research Center, Div 22/ Dept K4W, P.O. Box 218, MS 18-246, Yorktown Heights, NY 10598 USA

Si/SiGe modulation-doped layers have been harnessed to study the effect of growth interrupt on the epitaxial quality of layers grown by UHVCVD. Without any growth interruption, a mobility of about 1,900 cm^2/Vs (55,000 cm^2/Vs) is achieved at 300K (20K). The growth was interrupted at varying distance underneath the strain Si electron channel, while the wafers were pulled out to the load lock for 60 minutes. For an interrupt that is 200nm underneath the channel, there was no measurable effect on the mobility. However, interrupting the growth at 50nm, 10nm, and 0nm from the channel resulted in a mobility of 1,500, 1200, and 600 cm^2/Vs at room temperature, and 43,000, 8100 and 450 cm^2/Vs at 20K, respectively. The interrupt was associated with an oxygen spike in the SIMS profile amounting to a dose of 1 x $10^{13}cm^{-2}$. If, however, the wafers are cooled to 380C prior to growth interrupt while flowing SiH_4, the surface reamins hydrogen passivated, and the mobility increases from 600 cm^2/Vs to 1630 cm^2/Vs at 300K, and from 450 cm^2/Vs to 25,300 cm^2/Vs at 20K, for the case of interrupting the growth right underneath the channel. Thus the hydrogen passivation can be used as a valuable technique to interrupt the growth in case

intermediate processing is needed, or to purge the growth system from dopants, before growing undoped layers.

3:50 PM, H7

Characterization of Si/SiGe Heterostructures on Silicon-On-Sapphire Substrates: P. M. MOONEY[1]; J. A. Ott[1]; J. O. Chu[1]; J. L. Jordan-Sweet[1]; [1]IBM Research Division, T.J. Watson Research Center, Yorktown Heights, NY 10598 USA

Silicon CMOS on sapphire is one of the oldest silicon-on-insulator technologies and has excellent microwave characteristics. CMOS devices, which include a strained $Si_{1-x}Ge_x$ layer as the active channel, were successfully fabricated on improved silicon-on-sapphire (SOS) substrates [1,2]. SOS substrates and the $Si/Si_{1-x}Ge_x$ heterostructures grown on them by ultra high vacuum chemical vapor deposition (UHV/CVD) were characterized by both high resolution x-ray diffraction and transmission electron microscopy (TEM). A correlation between the densities of extended defects and the width of the x-ray rocking curve was found, allowing non-destructive evaluation of substrates by x-ray diffraction prior to epitaxial growth of the device structures. The improvement process [3] reduces the stacking fault density to levels below the detection limit of plan-view TEM, $<10^4$ cm^{-2}, and a corresponding reduction of the line-width of the x-ray rocking curve from 0.41° to 0.26° was observed. The remaining mosaic broadening arises from the presence of threading defects, typically in concentrations of 10^8 cm^{-2}. The SOS layer was nominally 100 nm thick; however, a thickness variation of about 30 nm was determined, typically in a bull's eye pattern centered on the 4" wafer, from the variation of the rocking curve intensity. Heterostructures for field-effect transistors (FETS) consist of an initial Si layer, followed by a 10 nm-thick $Si_{1-x}Ge_x$, layer, and a 15 nm-thick Si cap layer. The threading defects in the SOS substrate are, of course, replicated in the epitaxial layers but they apparently do not degrade the device performance. Despite the mosaic broadening of the x-ray rocking curves, the 10-nm $Si_{1-x}Ge_x$ layer can be seen as a shoulder on the peak of the underlying Si layer, when a rotating anode x-ray source is used. However, to obtain quantitative information on these heterostructures it is necessary to use a triple-axis x-ray diffraction configuration and a synchrotron x-ray source (beamline X20A at NSLS). The thickness and strain of the underlying Si layer, the thickness and composition of the $Si_{1-x}Ge_x$ channel and the thickness of the Si cap layer were extracted from the triple-axis x-ray spectra. The thermal stability of these heterostructures was investigated by annealing them in an inert atmosphere at 850 °C for an hour. A decrease in the Ge mole fraction and increase in the thickness of the $Si_{1-x}Ge_x$ layer were observed, indicating that out-diffusion of Ge from the strained SiGe layer occurs during annealing. The decrease in thickness of the Si cap layer was half of the increase in thickness of the $Si_{1-x}Ge_x$, layer indicating symmetric interdiffusion at both $Si_{1-x}Ge_x$ interfaces. The amount of interdiffusion was comparable to that reported for epitaxial quantum wells and superlattices on bulk Si substrates, suggesting that the extended defects do not play a significant role in the diffusion process. *Work supported under contracts N66001-95-C-6011 and DE-AC02-76CH00016. [1] S.J. Matthew, et al. Tech. Dig. 1997 Device Research Conference, 130 (1997). [2] S.J. Matthew, et al. submitted to Electron Device Letters [3] S.S. Lau, et al. Appl. Phys. Lett. 34, 76 (1979).

4:10 PM, H8+

Interactions of Misfit Dislocations with Ion-Implanted Species in Si/SiGe/Si (001) Heterostructures: ERIC A. STACH[1]; Robert Hull[1]; John C. Bean[1]; Kevin S. Jones[2]; Ahmed Nejim[3]; [1]University of Virginia, Department of Materials Science, Thornton Hall , Charlottesville, VA 22903-2442 USA; [2]Department of Materials Science, University of Florida , Gainesville, FL 32611 USA; [3]Department of Electrical Engineering, University of Surrey, Surrey, Guildford GU2-5XH United Kingdom

Quantitative understanding of the kinetics of misfit dislocation propagation is crucial to modeling the stability of metastably strained heterostructures as a function of time at temperature during both growth and post-growth annealing cycles. Following ion-implantation, misfit dislocation motion is dramatically affected by the presence of point defects created by the implantation process. The exact nature of this modification is a strong function of the implantation conditions and species. With this abstract we report measurements of the effect of emitter-contact and base-doping implantations on misfit dislocation velocities in Si / SiGe / Si (001). Boron doping implants into the base increase the overall relaxation rate of the structure due to increases in dislocation nucleation, but dislocation motion is slowed by interactions with the implantation-induced defects. Measurement of the dispersion of velocities caused by interactions between moving dislocations and the background point defect density show that there are different regimes of interaction. Despite the high stresses present in these structures dislocations may become pinned at clusters of defects for several seconds. The dislocations will eventually move, first gradually as they overcame the barrier presented by solute segregation to the dislocation core, then rapidly, until another defect cluster is encountered. This behavior is remarkably similar to that observed in steels, where "Cottrell atmospheres" of carbon impede plastic relaxation. Shallow BF_2 contact implantation results in drastically different behavior. Point defects created far from the strained base layer by the implantation process diffuse to the epilayer and cause very large increases in dislocation velocities, between five and eight times. This behavior has been examined as a function of implantation dose, current density and species. The velocity increase peaks as a function of dose, as with increasing point defect densities, dislocation - point defect interactions impede dislocation motion in a manner similar to that observed in the base implants. Additionally, as the current density of the implant is varied, different fluxes of point defects to the epilayer result, causing differing effects on dislocation motion. Equivalent energy fluorine, silicon, neon and boron implants indicate that fluorine is the species causing the observed velocity increase, possibly due to an electrical effect on the dislocation kink nucleation rate. These results show that quantitative in-situ transmission electron microscopy permits careful and detailed analysis of the fundamentals of dislocation - point defect interactions in semiconductor materials and aids in the successful modeling of strain relaxation in metastably strained structures.

4:30 PM, H9+

Low Threading Dislocation Density in Ge On Si: Control of Dislocation Pile-Up Formation In Relaxed SiGe Alloys: MATTHEW T. CURRIE[1]; Srikanth B. Samavedam[1]; Thomas A. Langdo[1]; Gianni Taraschi[1]; Eugene A. Fitzgerald[1]; [1]MIT, 77 Massachusetts Ave., Cambridge, MA 02139 USA

SiGe relaxed graded buffers function as templates for the integration of various devices on Si substrates, such as SiGe MODFETs, Ge photodetectors, and III-V LEDs and solar cells. However, high threading dislocation densities, dislocation pile-ups, and high surface roughness in the SiGe layers can impair device performance. In traditional graded structures, the density of dislocations in rare pile-ups can contribute significantly to the overall defect density, although these pile-ups are typically ignored in defect counting methods at high magnification (e.g. TEM). The pile-ups act as sources of threading dislocations in subsequent layers, thereby masking any processes contributing to the ultimate defect density in the field. We have demonstrated control of these problems by utilizing intermediate chemical-mechanical polishing (CMP) steps during graded buffer growth. The CMP process not only improves the material quality, but also allows us to investigate the processes which ultimately determine the minimum threading dislocation density. This technique has allowed us to produce high quality SiGe substrates of various Ge concentrations, including Ge on Si with a threading dislocation density of 2×10^6 cm^{-2} at the wafer scale. Data on pile-up and threading dislocation densities for 30%, 50%, 70%, and 100% GeSi on Si show unambiguously that a CMP step inserted within the graded buffer decreases the pile-up density as well as the number of threading dislocations in the pile-ups. Ge photodetectors on Si exhibiting record-low dark currents (2 orders of magnitude lower than that of any previously reported Ge photodetector on Si) have been fabricated, confirming the material quality of the SiGe graded buffers. Fabrication of SiGe MODFETs and GaAs LEDs on these relaxed buffers is also in progress.

4:50 PM, H10

Mesa Design for Dislocation Density Reduction of Relaxed SiGe Buffer Layers: DETLEV A. GRUTZMACHER[1]; Christian David[1]; Rainer Hartmann[1]; Elisabeth Müller[1]; Ulf Gennser[1]; [1]Paul-Scherrer-Institut, Micro and Nanostructures Laboratory, Würenlingen und Villigen, Würenlingen CH-5232 Switzerland

Recently it has been shown that the dislocation density of relaxed buffer layers can be reduced by the growth on small mesa structures. In our study we demonstrate that the size of the mesa can be drastically increased along certain crystallographic directions while maintaining the low dislocation density. Si/SiGe heterostructures consisting of a SiGe relaxed buffer layer and multiple Si quantum wells embedded in the topmost Ge layer were deposited by MBE on prestructured Si [001] substrates. Prior to growth, line shaped mesa structures with a length of 2mm and a width ranging from 2-10 micrometer were prepared by e-beam lithography and reactive ion etching. The orientation of the lines was

varied in steps of 15° from the [100] to the [010] direction. Structures varying in buffer layer thickness and with various Si well widths were deposited. The structural properties were investigated by TEM, AFM and x-ray diffraction. Low temperature photoluminescence (PL) was used to determine the optical properties. The AFM images reveal a clear dependence of the cross hatch pattern on the width and the direction of the lines. For lines parallel to the gliding planes of the dislocations the part of the cross hatch perpendicular to the lines is predominantly found, indicating an asymmetric relaxation mechanism. For lines which are 45° off from this direction, the cross hatch pattern is symmetric again. However the cross hatch pattern is largely reduced on top of the line shaped mesas compared to plane surface areas and apparently disappears completely for narrow mesa lines. This interpretation of the AFM data is confirmed by the TEM images, showing a drastic reduction of dislocations in the buffer layer grown on top of the mesa structure. TEM images show almost dislocation free SiGe buffers grown on the narrow 2 micrometer wide mesa lines. The improvement of the crystalline quality is also observed by the photoluminescence spectra. PL spectra of broad mesa lines show the typical broad luminescence obtained also from relaxed buffer layers grown on flat Si surfaces. The intensity of this broad luminescence decreases with decreasing mesa line width and a pronounced phonon resolved PL spectra is observed for structures grown on narrow lines. The energetic position of the spectra depends on the orientation of the mesa line. By varying the Si well width and by removing the quantum well structure a detailed analysis of the spectra in terms of PL of the Si quantum wells and of the relaxed buffer layer is made. Our experiments show that it is possible to prepare almost dislocation free SiGe buffer layers on mesa structures of infinite size in one direction and show a new way of controlling uniaxial strain by the adjusting the direction of the mesa on the surface. Thus viable routes for new electronic and optical devices are opened.

Wednesday PM, June 24, 1998

Session I. Materials Integration: High Dielectric Constant Materials

Room: 011
Location: Olsson Hall

Session Chairs: Laura Wills, Hewlett Packard Labs; D. G. Schlom, Penn State University, Department of Materials Science and Engineering, University Park, PA 16802-5005 USA

1:30 PM, I1*Invited

($Ba,Sr)TiO_3$ Capacitors for Ultra Large Scale Dynamic Random Access Memory - A Review on the Process Integration: CHEOL SEONG HWANG[1]; [1]Seoul National University, School of Materials Science and Engineering, San#56-1, Shillim-dong, Kwanak-ku, Seoul 151-742 Korea

Integration processes of the ($Ba,Sr)TiO_3$ (BST) capacitors for the next-generation dynamic random access memories (DRAMs) are reviewed. Various integration schemes utilizing different processes, different electrode materials and structures are reviewed from the point of view of the mass-production compatible process. The integration issues, mostly related to the electrode and the barrier material and their fabrication techniques, are described. Current status and problems of the two most viable techniques for the BST deposition, sputtering and metal-organic chemical vapor deposition (MOCVD), are comparatively described. Plate electrode technologies with the back-end processing issues are also briefly described, and some good experimental results are presented to show the feasibility of the BST capacitor.

2:10 PM, I2

Epitaxial BSTO Ferroelectric Capacitor for Giga-Bit Memory Applications: TAKASHI KAWAKIBO[1]; Kazuhide Abe[1]; Kenya Sano[1]; Naoko Yanase[1]; Noburu Fukushima[1]; [1]Toshiba Corporation, Materials and Devices Labs., R&D Center, Komukai Toshiba-cho 1, Saiwai-ku, Kawasaki, Kanagawa 210-8582 Japan

All perovskite ferroelectric capacitor cell was developed using a $SrRuO_3$/ ($Ba,Sr)TiO_3$/ $SrRuO_3$ heteroepitaxial technique on $SrTiO_3$ substrate. BSTO and SRO films were deposited continuously by rf magnetron sputtering method at 600 C. The Ba/Sr ratio in the BSTO film was adjusted by varying the rf powers for $BaTiO_3$ and $SrTiO_3$ targets. Every SRO and BSTO films were proven to be epitaxially grown in (001) cube on cube manner on the STO substrate. The full width at half maximum (FWHM) in the rocking curve was between 0.11 to 0.15 degree in both SRO and BSTO films. The c-axis lattice parameter of BSTO increased rapidly depending on the Ba content and reached 0.441 nm which was 8.6 % larger than the bulk lattice parameter, although the a-axis maintained almost same as those of the SRO film or the STO substrate. A series of very clear dielectric nature, from paraelectric in Sr-rich composition to ferroelectric in Ba-rich composition, was obtained. Relative dielectric constant showed its maximum of 870 at Ba content of 0.2, with film thickness of as thin as 20 nm. This is the largest storage capacitance so far. Ferroelectricity appeared at more than Ba content of 0.2, and remanent polarization and coercive voltage increased with Ba content. The maximum remanent polarization of 58 $\mu C/cm^2$ was observed at Ba content of 0.7, with film thickness of 20 nm. Again, This is the thinnest ferroelectric film so far. Asymmetry in the P-E hysteresis curve, however, was also appeared corresponding to coercive voltage. Symmetric electrode structure, i.e., SRO/BSTO/SRO did not improved enough the asymmetry in the hysteresis curve. Current epitaxial capacitor is very interesting on the following points in addition to its high dielectric constant or large remanent polarization; (a) all single domain and single crystal, (b) fully solid solution of $SrTiO_3$ and $BaTiO_3$, (c) elongated c-axis structure, (d) dielectric properties under strong electric field of more than 2MV/cm. These dielectric properties are well understood based on the displacement of the Ti ion and the apex O ion as a function of c-axis in the perovskite structure. DRAM application was also discussed. The “effective dielectric constant” was defined as a quotient of the total polarization in P-E curve by the voltage amplitude. Whereas maximum dielectric constant was obtained at Ba content of 0.2, the effective dielectric constant rapidly decreased with amplitude. The effective dielectric constant for ferroelectric capacitor became maximum when hysteresis curve was nearly saturated. At the amplitude of 1.5 Vp-p, the capacitor with Ba content of 0.3 showed the largest effective dielectric constant of 600, and it corresponded to the SiO_2 equivalent thickness of 0.12 nm. As a conclusion, the epitaxial BSTO capacitor is quite promising for giga-bit level DRAM and FRAM applications.

2:30 PM, I3

Low Barium Content, Barium Strontium Titanate Thin Films for Cryogenic Applications: FRANK DIMEO[1]; Steven M. Bilodeau[1]; Charles Seegel[1]; Jeffrey F. Roeder[1]; John Drab[2]; Michael Jack[2]; [1]ATMI, 7 Commerce Drive, Danbury, CT 06810 USA; [2]Hughes Santa Barbara Research Center, Santa Barbara, CA USA

The high dielectric constant of BST has made it the focus of intense research in order to realize higher storage densities for next generation DRAMs. However, other microelectronic applications such as integrating capacitors for infrared detector arrays would also benefit from increased storage density. These benefits include increased signal to noise ratios and expanded dynamic range. There is a unique set of issues associated with integrating BST with the detector electronics which include optimizing the storage capacity for use at cryogenic temperatures and reducing the thermal processing required to deposit high quality dielectric material. This paper will discuss our results in these areas using MOCVD to fabricate $Ba_{1-x}Sr_x$ TiO_3 thin films. It is well known that the peak in the bulk dielectric constant vs. temperature curve shifts to lower temperature with decreasing barium content. We have investigated the composition, thickness and temperature dependence of low barium content BST thin films. Low barium films with storage densities >53 fF/mm^2 from 40-80 K and leakage currents at 78 K of < 1 0^{-8} A/cm^2 at + 2 V and 100 s have been deposited. This is 10 x improvement in storage density over SiO_2 which would translate into a 10 x improvement in the signal to noise ratio in a detector array, when successfully integrated with CMOS electronics. To improve the integration of these films with current CMOS technology, we have also investigated the use of novel oxidation methods to reduce the deposition temperature of BST thin films to the range of 500-560℃. Deposition at this temperature expands the range of materials compatible with BST, and overcomes a major hurdle in incorporation of high dielectric materials in integrated circuits.

2:50 PM, I4+

The Dielectric Response of Epitaxial $BaTiO_3$: BRENT H. HOERMAN[1]; Soma Chattopadhyay[1]; Gregory M. Ford[1]; L. Kaufmann[1]; BRUCE W. WESSELS[1]; [1]Northwestern University, Materials Science and Engineering, 2225 N. Campus Dr., Evanston, IL 60208 USA

The frequency dependence of the dielectric response of ferroelectric thin films enables the determination of the important relaxation process. We have studied the frequency and temperature dependence of the dielectric constant for thin epitaxial films prepared by MOCVD using fluorinated precursors. Epitaxial layers were deposited on MgO and spinel. Using interdigitated capacitor structures, the complex impedance was measured over the frequency range of 10^3 to 10^7 Hz. For 320 nm thick films deposited on MgO, the in-plane dielectric constant was 500 and the dissipation factor was 5×10^{-2}. Films deposited on MgO and spinel with a thickness ~120 nm had a lower dissipation factor of 2.5×10^{-2}. The frequency dependence for all films was consistent with the Curie-von Schweidler response, which can be described as $e = e_0 - Aw^m$ where m was the order of 0.03. The temperature dependence of the dielectric frequency response was measured over the temperature range of 25 to 250ϒC. At temperatures above the ferroelectric-paraelectric phase transition, the low frequency dissipation factor increased significantly. Relaxation mechanisms responsible for the observed dielectric response will be discussed for layers deposited on the two types of substrates for different thicknesses.

3:10 PM Break

3:30 PM, I5

Influence of Top Electrodes on the Dielectric Behavior of MOCVD (Ba,Sr)TiO_3 Thin Films: SANDRA E. LASH[1]; Charles B. Parker[1]; Rene R. Woolcott[1]; Stephen K. Streiffer[1]; Angus I. Kingon[1]; Scott R. Summerfelt[2]; [1]North Carolina State University, Materials Science and Engineering, Box 7907, Raleigh, NC 27695-7907 USA; [2]Texas Instruments, 13536 PO Box 655012, MS 921, Dallas, TX 75265 USA

(Ba,Sr)TiO_3 (BST) is an important candidate material for use in dynamic random access memories and other integrated capacitor applications. Towards this end, extensive studies have been performed on the dielectric response of polycrystalline (Ba,Sr)TiO_3 thin films having Pt top and bottom electrodes. It is generally found that permittivity decreases with film thickness, although the origins of this behavior are not well understood. In order to determine possible mechanisms for this phenomenon, (001) fiber-textured BST films deposited at 640°C by liquid-source MOCVD on Pt/SiO_2/Si, were characterized with both Pt and Ir top electrodes on the same samples, for film thicknesses ranging from 30nm to 150nm, and Ti compositions of 51%, 52%, and 53.5%. As expected, the data for both types of structure lie on straight lines with non-zero intercepts when plotted as inverse zero-bias capacitance density versus film thickness. The slopes of these plots are similar for both capacitor structures (Ir/BST/Pt vs. Pt/BST/Pt), although the intercepts are larger for the case of Ir top electrodes. It is also found that the slopes increase with increasing excess Ti, while the intercepts are independent of Ti content within experimental error. Previous analysis of Pt/BST/Pt capacitors at non-zero fields indicates that this effect is not simply due to a series connected interfacial capacitance; however these results strongly suggest that the film electrode interface greatly influences the intercept of the inverse capacitance density versus film thickness. Further, Ir top electrodes are associated with an increase in frequency dependence of the permittivity over that for Pt, and concomitantly an increase in dielectric loss (approximately 1% for Ir top electrodes compared to 0.2-0.4% for Pt top electrodes). This may result from increased interfacial contamination, or because of the difficulty of properly annealing the Ir top electrode after deposition, without excessive IrO_2 formation. Both of these could lead to charge at the interface that acts to screen the polarization, or to a frustration of the ferroelectric soft mode near the interface, thus giving thickness-dependent properties, in addition to but distinct from interfacial capacitance effects. We will also discuss microstructural investigations of the electrode-film interface, focusing on differences between the two top electrode materials. The dielectric behavior as a function of temperature, applied field, and film thickness for the two cases will also be compared. This information will be used to identify factors that affect the thickness dependence of permittivity.

3:50 PM, I6

X-Ray Determination of Strain In LS-MOCVD (Ba,Sr)TiO_3 Thin Films: C. B. PARKER[1]; S. E. Lash[1]; R. R. Woolcott[1]; S. K. Streiffer[1]; A. I. Kingon[1]; [1]North Carolina State University, 229 Riddick Hall, 2401 Stinson Dr., Raleigh, NC 27695 USA

$(Ba_{0.7}Sr_{0.3})TiO_3$ thin films on Si are being investigated for use in DRAMs and other integrated capacitor applications. Typical MOCVD deposition temperatures for BST on Pt/SiO_2/Si are 640°C; therefore these films are under a large biaxial strain at room temperature because of the large difference in thermal expansion coefficient between the BST and underlying Si. This is expected to have a strong impact on film permittivity because of electrostrictive strain-polarization coupling. We have investigated this strain effect as a function of BST film thickness and Ti content, using x-ray diffraction via the d-spacing vs. sin2(psi) technique. The methodology of the measurement was as follows. The films measured ranged in thickness from 70nm to 120nm and had Ti contents from 51.0% to 53.5%. Diffraction measurements of plane spacings were made as a function of plane orientation in the film, thus determining the distortion of the BST unit cell relative to its assumed cubic state. These measured d-spacings were then normalized to a fictitious (100) spacing so that they could be directly compared. To convert these d-spacing measurements to strain, the unstressed lattice parameter is required. However, the bulk BST value could not be used as the films were grown under nonequilibrium conditions and were highly non-stoichiometric in Ti. Therefore, the unstressed lattice parameters were determined by estimating a stiffness tensor based on the bulk values of $SrTiO_3$ and $BaTiO_3$, and iteratively comparing calculated stresses with measured values [1]. It was found that the unstrained lattice parameter increased with increasing excess Ti from 0.3918 nm for 51%Ti, to 0.3985 nm for 53.5%Ti. The in-plane film biaxial strain also increased with increasing Ti content, from 0.4% for 51%Ti to 0.5% for 53.5% Ti. Comparisons based on mean field theory of the magnitude of the impact of strain on permittivity will be presented, relative to the measured dielectric behavior. Implications of these measurements for the method of accommodation of excess Ti in the film microstructure will also be discussed. [1] D.E. Kotecki, IBM, private communication.

4:10 PM, I7

A New Sputtering Method for High Dielectric and Low Leakage Current BST Thin Films: DEOK-SIN KIL[1]; Byung-Il Lee[1]; Seung-Ki Joo[1]; [1]Seoul National University, Div. of MS. & E., College of Engineering, San 56-1, Shillim-Dong Kwanak-ku, Seoul 151-742 Korea

$Ba_{0.5}Sr_{0.5}TiO_3$(BST) is a promising material for the next generation capacitors such as one Gbit or more due to high dielectric constant. It is well known that relatively high substrate temperature is required for good quality BST thin films due to their high crystallization temperature, however, high temperature processed BST films tend to show much higher leakage current due to their columnar structure in spite of high dielectric constant. In this work, the substrate temperature was changed to 350ϒC during sputtering after the deposition of very thin bottom layer (< 10nm) at 700ϒC. Deposition conditions of bottom layer were changed by varying the substrate temperature, thickness and deposition rate. In the case of 20nm thick BST thin films with 10nm thick bottom layer deposited at 700ϒC and at the rate of 0.25nm/min, SiO_2 effective thickness showed the value of 0.26nm and leakage current density exhibited the value of about 10^{-8} A/cm^2 up to 2.3 volt.

4:30 PM, I8

An Optically Addressed ZnO Ultraviolet Light Modulator with 10:1 Contrast: M. WRABACK[1]; H. Shen[1]; S. Liang[2]; C. Gorla[2]; Y. Lu[2]; [1]U.S. Army Research Laboratory, Sensors and Electron Devices Directorate, AMSRL-SE-EM, 2800 Powder Mill Rd., Adelphi, MD 20783 USA; [2]Rutgers University, Department of Electric and Computer Engineering, P.O.Box 909, Piscataway, NJ 08855-0909 USA

Zinc Oxide (ZnO) has recently received increasing attention due to the important role it may play in the emerging technology of blue and ultraviolet lasers and modulators. In this work we present an optically addressed ultraviolet light modulator which achieves a contrast ratio of 10:1 by exploiting the optical anisotropy in high quality (1,1,0) ZnO epitaxially grown on R-plane sapphire substrates by metal-organic chemical vapor deposition (MOCVD). The epitaxial relationships are [1,1,-2,0] ZnO parallel to [0,1,-1,2] Al_2O_3 and [0,0,0,1]ZnO parallel to [0,-1,1,1] Al_2O_3, as confirmed by X-ray diffraction (θ-2θ, and ϕ-scan) and high resolution cross-sectional transmission electron microscopy (HR-TEM) with selective electron diffraction. The thickness of the ZnO films is about 1 μm. Optical absorption measurements with linear polarized light impinging at normal incidence on this material indicate that a strong optical anisotropy exists which is most clearly manifested near the lowest exciton

resonances. This anisotropy in absorption is due to the polarization selection rules combined with the fact that the A and B exciton resonances are situated ~40 meV below the C exciton resonance. In the spectral region around the lowest exciton resonances light polarized parallel to the C-axis excites primarily C excitons, while light polarized perpendicular to the C-axis creates mainly A and B excitons. For light polarized at 45 degrees with respect to the C-axis, a polarization rotation away from the C-axis associated with the absorption anisotropy is observed which achieves a maximum of ~10 degrees at ~370 nm. The absorption anisotropy was modulated using 100 fsec pulses obtained by frequency doubling the signal beam of a 150 kHz optical parametric amplifier which were centered at the spectral position corresponding to the static rotation peak. A phase compensator and polarizer placed after the sample were oriented for minimum transmission of a weak test pulse incident on the material polarized at 45 degrees with respect to the C-axis. The transmission of the test pulse was monitored as a function of time delay τ between this pulse and a pump pulse with perpendicular polarization which generates an electron-hole pair density (~$10^{18}$$cm^{-3}$) sufficient to produce an anisotropic bleaching of the anisotropic absorption. This phenomenon creates an ultrafast dynamic rotation of the test pulse polarization manifested as a pulse width-limited rise in transmission through the crossed polarizer. A maximum contrast ratio of ~10:1, corresponding to a dynamic polarization rotation of 7 degrees, is observed at τ = 0. The turn-off time of the modulator is determined by the subsequent behavior of the induced transmission, which decays to half its maximum value within 18 psec, and reaches an equilibrium value after 100 psec.

4:50 PM, I9
Late News

Wednesday PM, June 24, 1998

Session J. Nanoscale Fabrication

Room: E316
Location: Thornton Hall

Session Chairs: Evelyn Hu, University of California, Santa Barbara, CA; Edward T. Yu, University of California, San Diego, CA

1:30 PM, J1
Nanometer Scale Ohmic Contacts to GaAs: DAVID B. JANES[1]; V. R. Kolagunta[1]; D. T. McInturff[1]; M. R. Melloch[1]; J. M. Woodall[1]; T. Lee[2]; R. Reifenberger[2]; J. Liu[3]; R. P. Andres[3]; [1]Purdue University, School of Elect. and Comp. Eng. and NSF MRSEC for Technology Enabling Materials, 1285 Electrical Eng. Bldg., W. Lafayette, IN 47907-1285 USA; [2]Purdue University, Dept. of Physics, W. Lafayette, IN 47907 USA; [3]Purdue University, School of Chemical Eng., W. Lafayette, IN 47907 USA

As semiconductor devices are downscaled, the demands on ohmic contacts will become more stringent. In particular, suitable contacts must provide low contact resistance in nanometer scale contact areas, and must be spatially uniform at the nanoscale. In compound semiconductor devices based on GaAs, conventional contacts such as alloyed Au/Ge/Ni on n-type layers are spatially nonuniform and also consume a significant surface layer in order to provide suitable specific contact resistivity. Nonalloyed contacts employing low-temperature grown GaAs (LT:GaAs) surface layers have been reported which can provide contact resistivities below 1e-6 ohm cm squared [1]. The nonalloyed nature of these contacts may make them appropriate for nanometer scale device applications, since they would not suffer from the deep interface and spatially nonuniform alloying found in Au/Ge/Ni contacts. The midgap states associated with excess As in the LT:GaAs can be observed using scanning tunneling microscopy (STM) even following air exposure of the samples [3], indicating that the LT:GaAs surface may be suitable for nanoscale contact applications which utilize techniques such as chemical self-assembly. Several device applications have been demonstrated for this contact [2], but to date, the spatial uniformity and performance as a nanometer scale contact have not been reported. In this presentation, we report the development and characterization of nanometer scale ohmic contacts to GaAs. The controlled geometry nanostructure consists of a single crystal gold cluster (4 nm in diameter), an organic interface layer and the LT:GaAs based contact structure [1-2]. Using ex-situ processing techniques, the LT:GaAs surface is coated with a self-assembled monolayer (SAM) of xylyl dithiol, which serves as a metal/semiconductor interface layer. Controlled size nanometer scale contact areas are defined by sparsely depositing gold clusters with diameters of 4 nm from colloidal suspension onto the interfacial monolayer. The xylyl dithiol molecules are 1.8 nm long and have thiol (-SH) end group at each end to provide chemical bonding to the GaAs and to the gold cluster surface. The interface layer provides effective mechanical tethering and strong electronic coupling between the gold clusters and the GaAs surface. The electrical characteristics (I-V) of the xylyl dithiol coated semiconductor regions and the cluster/interface layer/semiconductor structures are studied using a customized STM system. It is found that the gold cluster/xylyl dithiol/LT:GaAs system provides an effective nanometer scale ohmic contact to the GaAs, with good repeatibility between various clusters distributed on the surface. Although the tunneling resistance between the STM tip and gold cluster generally dominates the measured resistance, measurements at various tip to cluster spacings allow us to calculate an upper bound of 3e-5 ohm cm squared for the specific contact resistance between the gold cluster and the semiconductor structure. The contacts can handle current densities above 10 kiloamps amps per square cm, again presently limited by the STM measurement apparatus. MRM acknowledges support from AFOSR grant F49620-96-1-0234A. [1] M. Patkar, et al., Appl. Phys. Lett., 66, 1412 (1995). [2] V. R. Kolagunta, et al., 39th Electronic Materials Conference, 1997. [3] S. Hong, et al., Appl. Phys. Lett., 68, 2258 (1996).

1:50 PM, J2+
Argon Ion Damage and Exciton Localization Effects on the Luminescence of Self-Assembled Quantum Dots: W. V. SCHOENFELD[1]; Ching-Hui Chen[1]; P. M. Petroff[1]; E. L. Hu[1]; [1]University of California, Materials Department, Santa Barbara, CA 93106 USA

The growth of self-assembled InAs quantum dots (QDs) has recently been realized, allowing for new devices which could exploit their zero dimensional quantum confinement properties[1]. Processing of these devices often involves radiation exposure through dry etching or ion implantation. Previous studies have shown increased resistance of QDs to non-radiative surface recombination over quantum wells (QWs) due to their increased confinement[2]. One would expect to see a similar effect for QDs exposed to an Ar^+ plasma, which introduces non-radiative recombination centers in the form of point defects and defect clusters. This experiment compares the luminescence efficiency of a pseudomorphic $In_xGa_{1-x}As$ (x=0.2) QW and a QD layer after exposure to an Ar^+ =400 eV) plasma. The samples were composed of a reference InGaAs QW and an InGaAs QW or InAs QDs layer 500A below the sample surface. The reference QW deep below the surface was used in each sample to allow for normalization of the data. Both samples were exposed to varying doses (2-12 x 10^{15} cm^{-2}) of Ar^+ ions. The photoluminescence (PL) intensity as a function of increasing Ar^+ ion doses was found to decrease for both the QW and QDs layers. This is due to the correspondingly larger point defect concentration introduced for increased Ar^+ ion doses. In addition, the PL intensity of the QW layer was found to decrease much more rapidly than that of the QDs layer. We attribute this difference to the strong localization of excitons in the quantum dots[3]. To selectively probe only the effects of point defects in the QW and QDs regions, PL was carried out using selective pumping with a Titanium-sapphire laser (TSL). We will present a model of the QD behavior based on a recently developed ion damage simulation program. The greater resistance of the QDs to irradiation damage is attributed to exciton localization in the QDs. The data shows direct evidence of greater radiation resistance of the QDs relative to QWs due to zero dimensional quantum confinement in QDs. This characteristic suggests that structures based on QDs rather than QWs will retain better performances through subsequent irradiation steps used in device fabrication.

2:10 PM, J3
Nanostructuring by In-Situ Etching Within A III-V MBE System: H. SCHULER[1]; M. Lipinski[1]; T. Kaneko[2]; K. Eberl[1]; [1]MPI fuer Festkoerperforschung, Heisenbergstrasse 1, Stuttgart 70569 Germany; [2]Kwansei Gakuin University, Faculty of Science, Uegahara, Nishinomiya 662 Japan

The application of in-situ etching within a III-V MBE system on micromasked GaAs/AlGaAs layers and on self-assembled InAs quantum dots were investigated to study the potential for an advanced in-situ nanotechnology. The motiva-

tion of an in-situ technique is to avoid surface contamination, which is often a problem of ex-situ structuring processes. An in-situ etching system, which uses $AsBr_3$ as the etchant species was developed and integrated to a common III-V MBE system. In-situ etching with $AsBr_3$ allows layer-by-layer etching, inverse to MBE growth. Instant switching between growth and etching as well as simultaneous etching of GaAs/AlGaAs/InGaAs is possible. General properties like material selectivity for the different metal components as well as an anisotropy for different crystal planes will be discusssed. In-situ etching of SiO_2 masked (001) GaAs substrates produces extremely smooth (011) and (111) facets af [100] and [110] oriented SiO_2 stripes respectively. This is due to the anisotropy of the etching process, caused by the etching mechanism, which selectively removes the metallic surface atoms. A surface with a low content of metallic atoms shows a low etching rate and therefore is worked out during the etching process. The quality of the etched planes shows a high dependency on etching conditions especially on the substrate temperature. An application of such smooth facettes is an in-situ production of very sharp v-grooves as a base for the growth of quantum wire structures. AFM and TEM measurements of etched self assembled InAs quantum dots show the expected height reduction and a reshaping of the dots. The height reduction from 7 nm in the as-grown dots down to 4 nm after etching is confirmed by photoluminescence (PL) measurements, which show an energy blue shift in dependence of the etching duration. The PL line width of the dots is broadened from 50 meV of non-etched 2.8 monolayer InAs dots up to 80 meV after the removal of 0.5 monolayers of InAs indicating a broadening of the size distribution, while the peak intensity is reduced about 30%. The general properties of in-situ etching with $AsBr_3$ and first results from applications on InAs quantum dots and patterned substrates will be discussed.

2:30 PM, J4+

GaAs-Based Single Electron Transistors Based on Quantum Dot Formation by Schottky Wrap Gate: YOSHIHIRO SATOH[1]; Hiroshi Okada[1]; Kei-ichiroh Jinushi[1]; Tamotsu Hashizume[1]; Hideki Hasegawa[1]; [1]Hokkaido University, Research Center for Interface Quantum Electronics and Graduate School of Electronics and Information Engineering, North13, West8, Sapporo, Hokkaido 060-8628 Japan

Recently single electron transistors (SETs) have been intensively investigated from the viewpoint of constructing the next-generation electronics. In spite of the recent rapid progress in Si based SETs toward higher temperature operation, however, GaAs-based SETs reported so far operate mostly in the range of mK up to a few K because the conventional split gate control of two dimensional gas (2DEG) produces a rather weak and gradual confinement potential with soft-wall potential boundaries. Another serious issue common in semiconductor SETs is the difficulty in realizing voltage gains. To overcome these problems, we describe in this paper a new GaAs-based lateral SET based on quantum dot formation by Schottky wrap gates (WPGs). In this device, the potential profile within a heterostructure wire is controlled by three Schottky WPGs that run perpendicular to the wire direction and wrap around the wire except the bottom. Out of three WPGs, one center gate controls the potential of the dot, and two outer gates control the tunneling barrier profiles. Before fabrication of novel SETs, potential distributions in the device were calculated on computer, in order to confirm the formation of the dots and tunneling barriers. The computer simulation has shown that the center gate controls the electron number in the dot, being almost independent of the two outer tunnel barrier gates that basically control the tunneling barrier profile. According to results of simulation, dot sizes of 50 -100 nm and tunnel barrier heights of up to 80 -100 meV can be easily realized by using device future sizes of 70 - 150 nm. WPG controlled SETs were fabricated on AlGaAs/GaAs 2DEG wafers grown by standard MBE. A quasi-1DEG heterostrucure wire was formed by the electron beam (EB) lithography and the wet chemical etching. Three Schottky WPGs were formed by combining the EB lithography and the conventional Cr/Au lift-off process. The fabricated SETs having center gate lengths of 100 - 150 nm, showed clear and systematic appearance of Coulomb oscillation peaks of conductance up to 40 K. Thus, the new structure realized much stronger electron confinement in the dot than the previous split gate devices. In contrast to regular spacing and temperature-independent heights of conductance peaks in metal dot SETs, the present lateral GaAs SETs showed irregular gate voltage spacings and temperature-dependent heights of conductance peaks. This shows that the device operates in the quantum regime with shell filling. From the Coulomb diamond characteristics, a voltage gain significantly larger than unity was obtained for the first time as a semiconductor SET. This is due to tight charge control resulting from its FET-like structure of the device.

2:50 PM, J5

Collapse of Conductance Quantization in Schottky In-Plane-Gate Controlled GaAs Quantum Wires: JIN NAKAMURA[1]; Kei-ichiroh Jinushi[1]; Hiroshi Okada[1]; Hideki Hasegawa[1]; [1]Hokkaido University, Research Center for Interface Quantum Electronics, and Graduate School of Electronics and Information Engineering, North13 West8, Sapporo, Hokkaido 060-8628 Japan

To realize devices based on electron wave interactions, it is essential to understand fundamental quantum transport properties of long quantum wires having scattering centers. Ogata and Fukuyama have recently proposed that the one-dimensional system realized in a quantum wire having scattering centers can be regarded as a Tomonaga-Luttinger (TL) liquid, and they predicted collapse of conductance quantization in long quantum wires at low temperatures, due to mutual Coulomb interactions and impurity scattering. The purpose of this paper is to clarify experimentally the fundamental transport properties of long AlGaAs/GaAs quantum wires controlled by Schottky in-plane-gates (IPGs). IPGs are expected to realize stronger electron confinement than the conventional split gate structure. For sample preparation, standard electron-beam (EB) lithography and wet chemical etching were applied to form a quantum well wire on an MBE grown AlGaAs/GaAs single quantum well wafer. After formation of source and drain Ge/Au/Ni ohmic contacts on both ends of the wire, two Pt Schottky IPG electrodes were plated on the side edges of the wire by an in-situ electrochemical process. The electrochemical process realized a high Schottky barrier heights of 0.7 eV or higher on the heterostructure edge. The quantum wire transistor device showed good field effect transistor (FET) characteristics with the excellent gate control and pinch-off. Schubunikov-de Haas measurements showed that IPG changes the effective wire width without changing 2DEG sheet carrier density. The effective width of quantum wire was found to change linearly with the IPG bias. A quantized conductance was clearly seen for a sample with a channel length (L) of 1.6 micron meters up to 40 K. For another sample with L=1.0 micron meter, the conductance was quantized up to 100 K. From the shifts of plateau of conductance steps under the magnetic field, a subband separation in the IPG structure was found to be about 10 meV. This value is much larger than those obtained in conventional split-gate wires, indicating that stronger electron confinement can be realized by IPG. T h e heights of quantized conductance steps were found to be significantly smaller than the ideal value of $2e^2/h$, and the deviations increased with decreasing temperature. This temperature dependence of the quantized conductance was consistent with the predicted behavior by Ogata and Fukuyama based on the TL liquid picture. By applying the TL liquid theory to the observed temperature dependence, the value of the mean free path of the electron was estimated to be about 20 micron meters in the temperature range of 2 - 10 K.

3:10 PM Break

3:30 PM, J6

Longitudinal Quantized Magnetic Disks with Densities Up to 30 Gbits/in^2 Fabricated Using Nanoimprint Lithography: L. KONG[1]; X. Sun[1]; L. Zhuang[1]; M. Li[1]; S. M. Chou[1]; [1]Princeton University, Department of Electrical Engineering, NanoStructure Laboratory, Princeton, NJ 08544 USA

Quantized magnetic disks (QMDs) based on single-domain patterned magnetic nanostructures present a new paradigm for the magnetic storage with a density far beyond the fundamental limits of conventional thin film media [1,2]. Previously, we demonstrated the writing of longitudinal QMD, which consisted of Ni bars, with densities up to 7.5 Gbits/in^2 [3]. Here, we report the first fabrication and writing of longitudinal Co QMD with densities up to 30 Gbits/in^2. Longitudinal QMDs, consisting of rectangular Co bars, with densities up to 30 Gbits/in^2 were fabricated using nanoimprint lithography and a lift-off process. The fabricated Co bars have thicknesses varying from 35 nm to 10 nm, sizes from 400 nm x 100 nm to 145 nm x 35 nm, and spacings from 240 nm to 70 nm. Scanning electron micrographs (SEM) and atomic force microscope showed that each bit of the QMD was well defined. Magnetic force microscopy (MFM) indicated that the single domain was formed in the QMDs with densities up to 25 Gbits/in^2. For 10 Gbits/in^2 QMD, error-free writing with MFM was achieved, even though there was no feedback control of the writing tip position and even though the switching field of the Co bars was as high as 1020 Oe. This demonstrates that QMDs can relax the requirements on a writing head for ultra-high density magnetic recording. Based on our experiments, we believe that the MEM can write QMDs with much higher density. References[1] S. Y. Chou, M. S. Wei, P.R. Krauss, and P. B. Fischer, J. Appl. Phys., vol.76, pp. 6673, 1994. [2] S. Y. Chou, P.R. Krauss, and L. Kong; J. Appl. Phys., vol.79, pp.6101,

1996. [3] L. Kong, L. Zhuang and S. Y. Chou, WEE Trans. Magn., Vol.33, pp.3019, 1997.

3:50 PM, J7+

Magnetic Nanostructures Fabricated by Natural Lithography: JAMES L. WESTON[1]; Alejandro Butera[1]; John A. Barnard[1]; [1]The University of Alabama, Materials for Information Technology, Box 870209, Tuscaloosa, AL 35487-0209 USA

The next generation of magnetic recording media will require enhanced magnetic properties, such as an increased coercivity, as well as, improved recording properties, such as recording frequency stability and improved reading signal to noise ratio. One method for achieving these requirements is to introduce close-packed arrays of defects, such as holes, in a magnetic film. In earlier work, we used a used a nanoporous membrane as a substrate for sputtered magnetic thin films. Although this technique dramatically increased the coercivity, primarily due to shape anisotropy, the porous substrates were too rough to be used as a recording media and too irregular to be used to study the shape effects. To obtain a more ordered and smoother network structure, we have been using natural lithography to pattern and study hexagonal arrays of nanometer-sized holes in magnetic thin films. Natural lithography utilizes readily available aqueous solutions of monodisperse polystyrene latex spheres to form a lithographic mask. These spheres are available in a variety of sub-micron sizes with very a small degree of polydispersity. The spheres have a uniform surface charge which tends to repel them from one another in solution. However, when the solution is allowed to dry, the naturally repulsive spheres are brought together by the reduced surface free energy obtained by having spheres interrupt the solution-air interface. Under controlled drying conditions, such as we have achieved by slowly withdrawing a substrate from the solution, it is possible to coat the substrate with comparatively large domains consisting of a single layer of close-packed. Although it is possible to use these monolayers directly as a mask when depositing material, the resultant structures are not interconnected. To create an interconnected structure, it is necessary to "thin" the spheres. We have used oxygen-reactive ion etching to reduce the spheres and to open up gaps between adjacent spheres. In the next stage of lithography, a cobalt film is sputtered onto the surface of the substrate, coating both the thinned spheres and the revealed substrate. Finally, the spheres and the material deposited onto them are removed by ultrasonic agitation, leaving the magnetic material deposited between the pores as a network structure. The cobalt network structures that we have investigated are based on 300 nm spheres (to enable quick electron microscopy) with a 40-80 nm etched spacing between adjacent holes, corresponding to a porosity of ~ 20 %. What we have observed is the there is a significant increase in coercivity over continuous film behavior. This increase in coercivity is increased when the spacing between holes is decreased.

4:10 PM, J8+

Fabrication of Regular Arrays of Nanometer-Sized Pt Dots on III-V Substrates by Electron Beam Lithography and Electrochemical Deposition: TAKETOMO SATO[1]; Chinami Kaneshiro[1]; Hiroshi Okada[1]; Hideki Hasegawa[1]; [1]Hokkaido University, Research Center for Interface Quantum Electronics, Graduate School of Electronics and Information Engineering, North 13, West 8, Sapporo, Hokkaido 060-8628 Japan

A suitable formation technique of high-density regular arrays of size- and position-controlled nano-particles is necessary for high-density integration of single-electron transistors and memories. In this paper, we show that high-density regular arrays of Pt particles can be realized by the combining electron beam (EB) lithography and the in-situ pulsed electrochemical process. The novel electrochemical process in pulsed modes consists of pulsed anodic etching of semiconductors followed by subsequent in-situ pulsed cathodic deposition of metal in the same electrolyte. In the initial stage of deposition on unpatterned GaAs and InP substrates, nanometer-sized Pt particles with narrow size distributions have been found to precipitate on the substrates. Further deposition does not increase the size of Pt particles but increases the number of particles, eventually leading to full uniform coverage of the substrate by Pt nanoparticles. Furthermore, the size of Pt particles could be controlled by height, width and period of the pulses applied during deposition. It has been found that the particle diameter and its distribution-width became smaller with smaller pulse widths and longer pulse periods. The result indicates that the size distribution is determined by supply of metal-ion species at the semiconductor-electrolyte interface. High Schottky barrier heights (SBHs) of 1.07eV and 0.89eV have been realized for Pt/n-GaAs and Pt/n-InP diodes, respectively, by the optimized electrochemical process. In order to define dot-position, dot-array windows with a period of 100nm and density of $1x10^{10}cm^{-2}$ were patterned on GaAs by standard EB lithography before the electrochemical Pt deposition. Pt dots were then selectively formed only within windows, thereby realizing precise dot-position control. The SEM images show that Pt dots are formed in the center of the opened windows. In the case of EB-resist patterned substrate, the size of Pt dots have been found to increase in proportion to the number of the applied pulses. The smallest size of Pt dots formed by applying one pulse was 20nm. Furthermore, a scanned probe-contact measurement has shown that each nano-Pt/GaAs contact possesses good Schottky I-V characteristics with a high barrier height due to reduced Fermi-level pinning. These results show that high-density arrays of Pt nano-particles can be formed on III-V substrates with excellent controllability of the dot size and position by the number, height and width of pulses on the EB lithography patterned substrates. It seems that this new technique is promising for fabrication of arrays of single-electron transistors and memories.

4:30 PM, J9

Assembling Ordered Arrays of Silicon Nanoclusters in Zeolite: JILIANG HE[1]; Y. Ba[1]; C. I. Ratcliffe[1]; J. A. Ripmeester[1]; D. D. Klug[1]; J. S. Tse[1]; K. F. Preston[1]; [1]National Research Council of Canada, Steacie Institute for Molecular Sciences, 100 Sussex Dr., Ottawa, Ontario K1A 0R6 Canada

The encapsulation of semiconductor nanoclusters in the pores of zeolite has been actively explored as a means of producing tunable light-emitting materials. Zeolite is a type of crystalline aluminosilicate containing well-defined periodic cavities which can be utilized as ideal nanoreactors for the synthesis of semiconductor nanoclusters. This permits control of the encapsulated cluster's size and shape and enhancement the strength of optical signals through assembly of the clusters in an ordered array. We have synthesized luminescent silicon clusters within the diamond lattice of 13 Å supercages in zeolite Y through the chemical vapor deposition of disilane (Si_2H_6). The synthetic process was monitored by FT-IR, TGA-MS and solid state NMR. The initial step involves anchoring Si_2H_6 molecules to the zeolite framework at 100 ^oC. Multiple quantum ^1H NMR spin-counting shows that clusters of the anchored species in each supercage contain 38 H atoms, and thus about 14 Si atoms. Subsequent thermal treatment of the disilane-containing zeolite precursor led, via H_2 and SiH_4 elimination and Si clustering reactions to Si clusters. The formation of Si clusters is complete at 550 ^oC. These clusters are capped by H atoms and attached to the zeolite framework through SiO_x linkages. The average size of the resulting silicon clusters was determined by XPS and Si K-edge XANES. Both techniques give the same result, about 9-10 Si atoms per cluster. Since these two techniques have quite different sampling depth, i.e., ~ 50 Å for XPS and ~ 700 Å for XANES, this concordance indicates that the Si clusters are homogeneously dispersed in the zeolite host. The encapsulated Si clusters are air-stable and exhibit a room-temperature photoluminescence in the green-yellow region with a peak energy at about 2.2 eV. The band edges of the Si clusters were studied and compared with those of bulk Si (c-Si) by using synchrotron photoabsorption (Si K-edge XANES) and photoemission spectroscopies. The onset of the Si K-absorption edge in the Si cluster, corresponding to the conduction band (LUMO) minimum, is blueshifted 0.4 eV relative to that of c-Si, while the binding energy of the valence band edge indicates that the valence band maximum (HOMO) is 0.7 eV lower in the cluster than that in c-Si. Consideration of the relative shifts of the band edges together with the value of c-Si band gap (1.1 eV), leads to a HOMO-LUMO energy gap in the Si cluster of 2.2 eV. The close correspondence of the HOMO-LUMO energy gap and the photoluminescence peak energy confirms the origin of luminescence from the Si cluster as a predominantly e-h radiative recombination process. Tuning of the luminescence to the orange-red region was achieved by doping the Si clusters with P. These microcrystalline zeolitic Si cluster nanocomposites can be readily cast into films with organic polymers. Such materials may have potential applications in displays and lasers.

4:50 PM, J10

Self-Ordered Nanostructures: SUPRIYO BANDYOPADYAY[1]; Alexei Svizhenko[1]; Deyang Yu[1]; Latika Menon[1]; Albert E Miller[2]; Hsueh Chia Chang[2]; Gautam Banerjee[2]; Vadim Yuzhakov[2]; [1]University of Nebraska, Dept. of Electrical Engr., Walter Scott Engr. Center, Lincoln, NE 68588-0511 USA; [2]University of Notre Dame, Dept. of Chemical Engr., Fitzpatrick Hall, Notre Dame, Indiana 46556 USA

We will describe two electrochemical techniques for self-assembling highly ordered and periodic two-dimensional arrays of semiconductor, metallic and superconducting quantum dots. The first technique involves evaporating a thin film of aluminum on a conducting substrate and then electropolishing it in an organic, acidic solution to pattern the surface into a two-dimensional periodic array of crests and troughs with a pitch of about 100 nm. The troughs can be dissolved in very dilute bromine/methanol to leave behind the crests which form isolated metallic islands on the surface. These islands can be used as a self-assembled mask to mesa etch quantum dots underneath. The aluminum islands also form self-aligned electrical contacts to the dots. To our knowledge, this technique results in the most ordered arrays of self-assembled quantum dots reported to date. The second technique involves anodizing the electropolished aluminum in 15%sulfuric acid at a dc current of 40 mA/cm^2. This results in the formation of a nanoporous alumina film on the surface containing a regimented hexagonal array of pores. The pore diameter is 10$\pm$1 nm and interpore separation is typically 40$\pm$1 nm. The pores can be filled with the material of interest (semiconductor, superconductor, metal, etc.) by ac electrodeposition. This results in a quasi-periodic two dimensional arrangement of quantum dots dispersed in alumina. A first principle theory explaining the self-organization of the nanostructures (in the first technique) has been developed. The driving instability of the pattern formation is the preferential adsorption of polar organic molecules on surface ridges which are protected from dissolution. This instability is balanced by surface diffusion of the adsorbate to yield a length scale of $4\Pi(D_s k_d)^2$, where D_s is the surface diffusivity and k_d is desorption coefficient of the adsorbate, which correlates well with the measured pitch. Quantum dots self-assembled by these techniques have been directly imaged with AFM, TEM and field emission SEM, and characterized by energy-dispersive analysis of x-ray and Auger spectroscopy for determining chemical composition. Additionally, their optical, magnetic, superconducting and electronic properties were probed by degenerate pump-probe spectroscopy, ac susceptometry, magnetoresistance measurements, SQUID techniques and capacitance-voltage measurements. Some of these measurements have revealed intriguing signatures of quantum confinement effects. These include a five-fold increase in the non-linear second-order dielectric susceptibility$\chi^{(2)}$ associated with giant dipole transitions between quantized subband states in the quantum dots, and a large blue-shift in the optical spectra caused by electron and hole confinement. Other intriguing transport effects have been observed and can be used to realize ultra-dense memory with long retention times. These results and their associated physics will be discussed.

Wednesday PM, June 24, 1998

Session K. Materials Issues for SiC Device Processing

Room: 009
Location: Olsson Hall

Session Chairs: Karen Moore, Motorola Inc., Tempe, AZ 85284; Michael Capano, WL/MLPO, WPAFB, OH 45433-7707 USA

1:30 PM, K1

A Time-Dependent Dielectric Breakdown (TDDB) Study of Thermally Grown SiO_2 On 6H-SiC: M. M. Maranowski[1]; J. A. COOPER[1]; P. Gosavi[1]; [1]Purdue University, School of Electrical and Computer Engineering, West Lafayette, IN 47907-1285 USA

In this presentation we report a study of the time-dependent-dielectric-breakdown (TDDB) of thermally grown oxides on 6H-SiC. Starting wafers are Si-face 6H-SiC substrates with 3 μm epilayers doped 2x10^{16} cm^{-3} with N (n-type) or Al (p-type). Samples are RCA cleaned and loaded into a resistance-heated quartz furnace tube under O_2 at 850 ϒC to minimize Si depletion from the surface. The temperature is raised to 1150 ϒC and the samples are oxidized in wet O_2 (bubbler), followed by a 30 min. in-situ Ar anneal. The furnace is cooled to 900 ϒC and the samples removed. Polysilicon is deposited by LPCVD at 625 ϒC and doped with P spin-on dopant, driven in at 900 ϒC. Oxide thickness ranges from 151 to 555 Å, and the MOS capacitors have interface state densities around 1.5x10^{11} eV^{-1}cm^{-2} on both n-type and p-type SiC. TDDB data is taken using an automated constant-voltage stress technique. Measurements are conducted on individual die containing 40 MOS capacitors, 120 μm in diameter. Data is obtained for n and p-type capacitors under positive (negative) bias stress (surface accumulated) at 145, 240, and 305 ϒC and oxide fields between 6 - 9 MV/cm. Failure distributions show typical bimodal failure characteristics, similar to that observed on silicon. The early portion of the distribution represents extrinsic failures due to processing-induced point defect within the oxide, while the later portion represents intrinsic failure of the oxide itself. The failure distributions are separated into intrinsic and extrinsic parts and the mean-time-to-failure (MTTF) of each part is plotted as a function of oxide field. These data can be extrapolated to at-use electric fields (3 - 5 MV/cm) to obtain predictions of MTTF at these fields. Briefly summarized, our results indicate that positive bias stressing is more damaging than negative bias stressing. This is expected because positive stressing causes electron injection from the SiC into the oxide, and the conducdon-band barrier for electron injection from SiC to $Si0_2$ is lower than from Si into SiO_2 due to the wider bandgap of SiC. Interestingly, the field acceleration factor for SiC is higher than for Si, so that MTTF increases faster as field is reduced. At high oxide fields (8 - 9 MV/cm) the MTTF for SiC is shorter than for Si, but as the field is reduced to 3 - 5 MV/cm, the MTTF of SiC becomes comparable to Si. For example, at 4 MV/cm the MTTF for intrinsic failures on n-type 6H-SiC are approximately 10 and 10,000 years at 250 and 145 ϒC, respectively. These results are very encouraging for the prospects for MOS-based power switching devices in SiC. This work is supported by grants from ONR (MURI), BMDO/IST, and SRC.

1:50 PM, K2

Fowler-Nordheim Hole Tunneling Through SiO_2 On p$^+$ 6H-SiC: RICHARD WATERS[1]; Bart VanZeghbroeck[1]; [1]University of Colorado, Dept. of Electrical and Computer Engineering, Boulder, CO 80309-0525 USA

SiC possesses a wide bandgap and high thermal conductivity which makes it a prime candidate for high power and high temperature electronics. In addition, the ability to grow thermal oxides on SiC is extremely attractive for the fabrication of MOS devices. The quality of the oxide, however, plays a crucial role in determining the maximum temperature and electric field before breakdown occurs. In particular, the possibility of hole tunneling in p-channel MOS devices due to the large bandgap of SiC must be considered. In this paper, we present F-N tunneling of holes through thermally grown SiO_2 on p$^+$ SiC. The fabricated structure consisted of a thin oxide grown on a p$^+$n SiC junction at 1100ϒC for 10 minutes in a pyrogenic water vapor atmosphere. Ellipsometry measurement of the oxide yielded a thickness of 10.1 nm and an index of refraction of 1.457. The thickness of the p$^+$ layer was 0.17 mm. A Cr/Au contact on top of the SiO_2 served as a gate contact for the MOS structure while Al/Ti/Au and Al were used to contact the p$^+$ (base) and n (collector) regions respectively. The measurement of the tunneling current was conducted by applying a positive potential to the gate contact with reference to the base while reverse biasing the p+n junction. In the absence of recombination within the base, the p$^+$n junction served as a means to separate the hole and electron tunneling currents. Our experimental results revealed that the base (hole) current was an order of magnitude larger than the collector (electron) current. The effective barrier heights and masses of the carriers in SiO_2 were obtained by fitting a Fowler-Nordheim curve to the base and collector currents. The extracted barrier height and effective mass for holes in SiO_2 were 2.56 eV and 0.89 m_o respectively. Similarly, the extracted barrier height and effective mass for electrons were 3.7 eV and 0.42 m_o respectively. Both theoretical F-N curves give excellent agreement with the experimental data over three decades of current. In addition, the values used to fit the F-N curve to the electron current are well established thus confirming the assumption that recombination within the p+ base is negligible. The electric breakdown field of the SiO_2 was found to be approximately 1.1 MV/cm^2 for all devices tested which is an agreement with previously reported values of the breakdown field of SiO_2 on SiC. [1] In summary, we have observed hole tunneling through thin oxides grown on p$^+$ SiC. We have found that for positive gate bias the dominant current mechanism through the oxide is hole current due to the low barrier height encountered by the holes. This large hole current at relatively low voltages, 50 nA at 11 V, is a cause of concern for the future development of p-channel MOS devices in SiC. [1] A. Agarwal et. al. "Temperature Dependence of Fowler-Nordheim Current in 6H- and 4H-SiC MOS Capacitors" Electron Device Letters, vol.18, no. 12, pp 592-594, 1997. * Funded by Astralux Inc., Boulder, CO 80303

2:10 PM, K3

Deep Defect in P-Type 6H-SiC Revealed by Optical Characterization of GaN/SiC n-p Heterojunctions, SiC n-p Junctions And p-SiC : JOHN T. TORVIK[1]; Chang H. Qiu[1]; Moeljanto W. Leksono[1]; Jacques I. Pankove[1]; [1]Astralux Inc., 2500 Central Ave., Boulder, CO 80301 USA

GaN and 6H-SiC are important materials for high temperature and high power electronic device applications. Deep defect levels are a concern particularly in bipolar devices. Optical characterization of GaN/SiC n-p heterojunctions, SiC n-p junctions and p-SiC was performed to verify the presence of a deep defect located ~ 1.25 eV above the valence band edge (VBE) in p-type 6H-SiC. The GaN epitaxial layers for this study were grown by MOCVD on commercial SiC substrates. The sample structures consist of a ~1-um-thick n-type (1-5x$10^{18}$$cm^{-3}$) GaN epi-layer grown directly on bulk p-type (5-18x10^{17} cm^{-3}) Si-face 6H-SiC. The GaN was unintentionally doped; nucleation (buffer) layers were not used. The GaN exhibited strong near-band edge photoluminescence and weaker broad defect-related yellow luminescence. Diode mesa structures were defined using reactive ion etching, and metal contacts were formed using the standard photoresist lift-off technique. The first suspicion of a parasitic deep level in p-type SiC appeared in the I-V characteristics of the n-GaN/p-SiC heterojunctions. The current under forward bias appears from the noise level (~1 pA) at ~1.15 V instead of the expected 2.5 V as calculated from drift/diffusion theory. The built-in potential of these junctions is about 2.9 eV as measured by capacitance-voltage measurements. The current is believed due to tunneling of electrons from the conduction band edge of GaN into a defect level located 1.25 eV above the VBE in p-SiC. The difference between the 1.15 V current onset and the defect level location is due to ~0.1 eV separation of the Fermi level and the VBE in the p-type SiC. The presence of a deep level in p-type 6H-SiC located ~ 1.25 eV above the valence band edge was verified by luminescence spectroscopy of GaN/SiC heterojunctions, SiC homojunctions and p-SiC. Electroluminescence (EL) measurements on the GaN/SiC heterojunction diodes revealed a strong infrared peak at 1.25 eV, and a weaker red peak at 1.75 eV. To exclude the GaN/SiC growth interface as the origin of the observed EL, the experiment was repeated on SiC n-p homojunctions. The SiC homojunctions exhibited EL peaks at 1.15 eV and 1.85 eV. Furthermore, photoluminescence (PL) measurements of p-SiC yielded peaks at 1.25 eV and 1.80 eV. It is concluded that since the bandgap of 6H-SiC is 3.03 eV, the EL and PL peaks are radiative transitions from the conduction band edge to a defect level and subsequently down to the valence band edge of p-SiC. This defect level is located 1.25 eV above the valence band edge. Possible origins of this level will be discussed.

2:30 PM, K4+

Reoxidation Characteristics of Oxynitrides on 3C- and 4H-SiC: KIRAN V. CHATTY[1]; Vishnu K Khemka[1]; T. Paul Chow[1]; R. J. Gutmann[1]; [1]Rensselaer Polytechnic Institute, Center For Integrated Electronics, CII-6015, 110, 8th street, Troy, NY 12180 USA

Silicon Carbide (SiC) is fast becoming one of the most popular choices for high voltage and high power devices. The high avalanche electric breakdown field, large saturating electron drift velocity and high thermal conductivity of SiC are attractive for high power applications. An important advantage of SiC is the ability to grow a thermal oxide on its surface. It is perhaps the only other semiconductor besides Silicon (Si) on which a stable thermal oxide (SiO_2) can be grown. This opens up a plethora of opportunities to fabricate MOS devices and to take advantage of their superior intrinsic characteristics. However the SiO_2 films grown on SiC especially on the p-type are generally of poor quality due to high density of fixed oxide charges and interface traps. Recently, it has been shown that nitridation of oxide on silicon resulted in a dramatic improvement in their electrical characteristics. The incorporation of nitrogen into the SiO_2-Si interface improves the breakdown characteristics and immunity to hot carrier damage. Nitridation of SiO_2 films has also been applied to the case of SiC with some success. The nitridation is accomplished by oxidation/annealing of the films in N_2O or NO. The presence of nitrogen at the interface improves its electrical characteristics, but its incorporation in the bulk can degrade its performance. While N_2O oxidation of oxides in both Si and SiC resulting in a similar accumulation of nitrogen at the semiconductor- oxide has been reported, the reoxidation of the resulting oxynitride layer thus formed has not been studied. This paper presents, for the first time, the reoxidation characteristics of 3C and 4H-SiC polytypes and demonstrates that they are quite different than those in silicon. Secondary Ion Mass Spectrometry(SIMS) has been used to evaluate the depth profiles of the oxynitride films on both Si and SiC. In Si, the stability of the nitrogen incorporated into the interface is dependent on the oxidant flow rate. In particular, the nitrogen at the interface is unaffected if the reoxidation is carried out at high flow conditions. With SiC, as shown in this paper, the interfacial nitrogen is much less stable. Complete depletion of the nitrogen from the interface has been observed with the reoxidation of SiC oxynitrides for both 3C and 4H polytypes. The interfacial nitrogen in silicon oxynitrides is triply bonded to the silicon, but it appears from the above experiments that the interfacial nitrogen bonding in SiC oxynitrides is more complex with the nitrogen bonding to both silicon and carbon. We are currently examining the interfacial bonding using X-ray Photoelectron Spectroscopy(XPS). We are also investigating the stability of the oxynitride relative to the reoxidation temperature, oxidation ambient and flow rate. Acknowledgment: This work is supported by Philips Research Laboratory, NY, USA and MURI of the Office of Naval Research.

2:50 PM, K5

Numerical Demonstration of the Impact of Material Parameter Uncertainty on A Passivated 4H-SiC Thyristor's Steady State Characteristics: PANKAJ B. SHAH[1]; Kenneth A. Jones[1]; [1]U.S. Army Research Laboratory, Sensors and Electron Devices Directorate, AMSRL-SE-RL, Adelphi, MD 20783 USA

There is great interest in silicon carbide (SiC) high temperature, high power, and high field breakdown capabilities. Thyristors, and gate-turn-off (GTO) thyristors, provide high-power and high-speed switching capabilities. An investigation of the 4H-SiC material-parameter uncertainty's impact on thyristor performance is needed because 1) material parameters vary across a uniformly processed wafer, 2) most material parameter values are measured on exposed single film layers, not buried layers, and 3) it is difficult to measure, but important to know, how the material parameters in different regions of a thyristor change during growth and processing. For this, two-dimensional drift-diffusion model based numerical simulations are done for an interdigitated four-anode three-gate 4H-SiC thyristor passivated with SiO_2 and fabricated at CREE Research. Material parameters are obtained from the literature for concentration and field dependent mobility, impact ionization, Shockley-Read-Hall recombination with concentration dependent lifetime, and silicon based models for Auger recombination rate and band gap narrowing. SiO_2/SiC interface charge and recombination velocity are included. Results explain the experimentally measured small and large steps in the breakover voltage and switching current of I-V curves traced at equal increments of gate current. For the structures grown at CREE, results indicate free carrier lifetimes on the order of two microseconds. Results focus on the on-state and negative differential resistance (NDR) portions of the thyristor I-V curve, because these provide good information about the material quality and device performance. Results demonstrate that with increasing electron and hole lifetimes, the NDR region I-V characteristic exponentially approaches a single curve regardless of whether the electron lifetime is five times the hole lifetime, or whether the hole lifetime is twice as long as the electron lifetime. Also, the NDR portion of the I-V curve has high and low slope regions that provide easily accessible information about the material, and can be mapped by measuring the I-V curve for different gate drive currents. Considering the interface, increasing the surface recombination velocity from 500 cm/s to 50,000 cm/s reduced the slope in the high slope portion in the NDR region and increased the holding current, while breakover voltage stays constant, on the zero gate current curve. As the interface charge increased from 1x10^{11} to 9x10^{11} cm^2, the breakover voltage on the zero gate current I-V curve decreased from 1,030V to 125V, but the holding current remained constant. Also, the amount of interface charge is more critical than its sign. Furthermore, it was observed that deeper lying donors decreased the holding current while deeper lying acceptors increased the holding current, though in both cases the breakover voltage with zero gate bias wasn't affected. Changing other material parameters had minor effects. The reasons these changes occurred as well as parameter requirements for GTO operation will be discussed.

3:10 PM Break

3:30 PM, K6

Surface Morphology of Ion Implanted Silicon Carbide: M. A. CAPANO[1]; Sei-Hyung Rei[2]; J. A. Cooper[2]; M. R. Melloch[2]; [1]Air Force Research Laboratory, AFRL/MLPO, WPAFB, OH 45433-7707 USA; [2]Purdue University, School of Electrical and Computer engineering, West Lafayette, IN 47907-1285 USA

The fabrication of many SiC electronic devices require selective doping of epitaxial layers that can only be achieved by ion implantation. While n-type doping of SiC with N implantation is well established, implantation of boron and aluminum acceptor species is a more serious problem. Activation levels for

acceptors are frequently reported to be less than 10%. Unacceptably low inversion-layer electron mobilities in implanted p-well regions of many MOS devices are also a serious problem. Low inversion-layer mobilities are responsible for high on-resistances observed in SiC power devices which otherwise reveal outstanding blocking voltage characteristics. Roughening of the surface region following implant activation annealing may be the cause for the low mobilities. The objective of this presentation is to examine which processing variables are dominant in achieving high activation levels for boron and aluminum implants into SiC, and to investigate how processing under conditions necessary to yield high activation affects surface morphology. Results from Normarski differential interference contrast optical microscopy, atomic force microscopy (AFM), capacitance-voltage (CV) measurements, and transmission line measurements (TLM) are discussed and compared to recently published data. Boron implantation into 4H-SiC and post-implant annealed in argon is emphasized in this study. Implant activation was 1% following a 40 min anneal at 1500 ϒC. The activation level increased as the annealing temperature increased. After 1600 ϒC annealing for 40 min, the activation was 13%, and complete activation of B in 4H-SiC was achieved after annealing at 1750 ϒC for 40 min. Annealing in argon at temperatures resulting in high (>50%) activation are shown to be damaging to the surface of 4H-SiC. Measured rms surface roughnesses following B implantation prior to annealing are 0.7 nm. The roughnesses increase to 2.3 nm, 5.8 nm and 10.1 nm following 40 min anneals at 1500 ϒC, 1600 ϒC, and 1700 ϒC, respectively. Additional experimental data for 6H-SiC is also considered. Sheet resistances for Al implants (5 x 10^{19} cm^{-3}) were 54.4 kW/(after annealing in argon for 40 min at 1600 ϒC, and 32.2 kW/) after 1800 ϒC annealing for the same time. Roughnesses corresponding to these anneals are 11.1 nm and 21.2 nm, respectively. The observed roughening is caused by step bunching. A model is proposed to describe the roughening phenomenon. The premise of the model is that SiC sublimation and mobile surface molecules enable the surface to reconfigure itself into an equilibrium form. Evidence is presented that clearly demonstrates that roughening is dependent upon implant damage and the annealing environment. Samples annealed in silane or a physical-vapor-transport ambient show improved surface morphologies compared to samples annealed in argon, consistent with the model.

3:50 PM, K7

Low On-Resistance, Low Leakage 4H- And 6H-SiC p-n Junction Diodes Created By C And Al Co-Implantation: KIYOSHI TONE[1]; Hakim Hussain[1]; Maoyou Sun[1]; Jian H. Zhao[1]; [1]Rutgers, the State University of New Jersey, Department of Electrical and Computer Engineering, P.O. Box 909, Piscataway, NJ 08855-0909 USA

Production of high-quality p^+-n diodes is one of the most essential requirements for the anticipated development of SiC-based bipolar power electronics. In this work, high-concentration p-type doping by C-Al co-implantation, which has been shown to be effective in reducing p-type contact resistance [1,2], is successfully applied to anode formation in 4H- and 6H-SiC diodes. Excellent I-V characteristics with almost negligible contact resistance and leakage currents comparable to the best of previous reports have been obtained. Multiple-energy (20-200 keV) implantation of C and Al was performed on 4H- and 6H-SiC n/n^+ epitaxial wafers at room temperature (RT) or 600ϒC to produce 0.2-μm deep box profiles of C and Al at equal concentrations ranging from 1 to 20x10^{20} cm^{-3}. Following post-implantation annealing at 1500ϒC for 30 min in Ar ambient with SiC powder, the implanted wafers were processed into mesa diodes of 90-180 μm in diameters by using inductively-coupled plasma etching. The p- and n-type ohmic contacts formed by deposited Al and Ni, respectively, were annealed at 950ϒC for 5 min in Ar. As control samples, diodes without C implantation were also prepared. I-V characterization of the 6H-SiC diodes from -100 to +3 V shows a tendency of reverse leakage current reduction by the use of C-Al co-implantation in comparison to Al-single implantation. The best result is obtained in the diodes co-implanted at RT with an equal C and Al concentration of 8x10^{20} cm^{-3}. The leakage current of 5.3 nA/cm^2 obtained at -100 V is comparable to the levels of low-leakage implanted diodes reported in the past, including B-implanted diodes [3,4]. Although B is considered to give lower leakage currents [3,5], our results indicate that this may not necessarily be the case. The significance of the use of the shallower acceptor Al is seen in the forward characteristics, where the on-resistance of 4.3 mΩcm^2 is limited by the resistance of the n-epitaxial layer, not by the contact resistance of Al, which is in the 10 μΩcm^2 range as measured by the transferred-length method on the same wafer. Low-leakage diodes are also obtained in 4H-SiC, where a leakage current of 9.0 nA/cm^2 is observed at -100 V in the diodes co-implanted at RT with an equal C and Al concentration of 1x10^{21} cm^{-3}. The on-resistance is further decreased in 4H-SiC to 0.60 mΩcm^2, partly owing to the increased mobility in 4H-SiC. [1] Zhao et al., IEEE Electron Device Lett. 18 (1997), p. 375. [2] Tone et al., Electron. Lett. 33 (1997), p. 1904. [3] Ramungul et al., Silicon Carbide and Related Materials '95 (1996), p. 713. [4] Hölzlein et al., ibid. '95 (1996), p. 561. [5] Takemura et al., ibid. '97.

4:10 PM, K8+

Characterization of Phosphorus Implantation in 4H-SiC: RUPAL K. PATEL[1]; V. K. Khemka[1]; N. Ramungul[1]; T. P. Chow[1]; Mario Ghezzo[2]; Jim Kretchmer[2]; [1]Rensselaer Polytechnic Institute, Center for Integrated Electronics, CII-6015, 110, 8th Street, Troy, NY 12180-3590 USA; [2]General Electric Corporate Research & Development, Schenectady, NY 12301 USA

Silicon carbide is an attractive semiconducting material for devices operated at high-voltage and high-temperatures. Ion-implantation has been shown to be the only viable mean for selective area doping in SiC, as dopant diffusion is extremely slow even at high temperatures (<1800°). While nitrogen is most widely employed as an n-type dopant in 4H-SiC and there have been few reports on implantation of phosphorus in 6H-SiC, no work has yet been reported on 4H-SiC. Also, the electrical characteristics of phosphorus implanted high-voltage SiC junctions are yet to be reported. We have investigated phosphorus implantation in 4H-SiC using analytical techniques (SIMS,TEM) and have subsequently fabricated high-voltage junction rectifiers. Implanted layers and diodes have been characterized with 4-point sheet resistance measurements and forward and reverse characteristics as well as reverse recovery measurements. N^+P junction rectifiers and test structures have been fabricated using a mesa-isolated process on a commercial Si face, p on p^+ 4H-SiC wafer. The thickness and the doping of the p-epilayer and p^+ substrate are 4 micron, 1.8E16 cm^{-3}, and 370 micron, 8.2E17 cm^{-3}, respectively. N^+ layer was formed by multiple phosphorus implantations with varying energies and different total dosage to study the dosage dependency. Phosphorus was also implanted to form the Junction Termination Extension (JTE). All implants were activated by annealing the samples at 1600° for 10 min in Ar. Ni-based and Al-based metallization schemes were utilized to form the n- and p-type ohmic contacts, respectively. Sheet resistance of the n^+ implanted layer was measured using mesa-isolated van der Pauw (one square, 70 micron sqaures) and Hall effect (4 squares, 50 micron squares) structures. At room temperature, the measured sheet resistance was as low as 160 ohms/sq. This value of the sheet resistance is the lowest ever reported for any dopant in any SiC polytype. Specific contact resistivity of the n-type contact on the implanted layer was 4E-5 ohms.cm^2. SIMS analysis of the as implanted and annealed samples indicated phosphorus diffusion after high temperature anneal leading to a surface concentration decrease. A bright blue light emission was observed from all diodes when biased to a forward voltage greater than 3 V. Typical forward log(J)-V characteristics of the rectifiers showed a conduction region followed by a high-current saturation region. The log(J)-V curves in the conduction region are linear over seven decades and show two distinct regions with different slopes. The ideality factor (n) decreases from a value of 2 at lower currents indicating the space-charge recombination limited current, to a value of about 1.3 at higher currents that agrees with a generalized Shockley-Noyce-Sah (SNS) multiple-traplevel recombination model. Measurements of reverse leakage currents of the rectifiers indicate that diodes with a lower phosphorus implantation dosage yield lower leakage currents. High leakage currents in the rectifiers with a higher phosphorus dosage is attributed to a higher implantation damage. These leakage currents were found to be relatively insensitive to the increase in temperature. Small area (225 micron diameter) rectifiers exhibited a reversible breakdown voltage as high as 625 volts. This high breakdown voltage is approximately 90% of the theoretical breakdown voltage (~ 675 V) for a punch-through rectifier with the aforementioned specifications. Positive temperature coefficient of the breakdown voltage was observed in these rectifiers. The minority carrier lifetime extracted from the reverse recovery switching transient was also used to evaluate the quality of the implanted junctions. The rectifiers with lower phosphorus dosage were switched from a forward current density of 500 A/cm^2 to a reverse voltage of 100 V. The lifetime was extracted to be about 150 ns. Lifetime was also analyzed as a function of the forward current density and temperature. This work is supported by the MURI of the Office of Naval Research (subcontracted from Purdue University) and DARPA (subcontracted from GE CR&D).

4:30 PM, K9

Ion-Implantation Induced Damage in 6H-SiC: The Influence of Substrate Temperature: H. WIRTH[1]; W. Anwand[1]; A. Mucklich[1]; D. Panknin[1]; M. Voelskow[1]; G. Brauer[1]; W. Skorupa[1]; O. Gonzalez-Varona[2]; A. Perez-Rodriguez[2]; [1]Forschungszentrum Rossendorf, PF 510119, D-01314 Dresden, Germany; [2]Universitat de Barcelona, Av. Diagonal 645-647, E-08028 Barcelona Spain

Because of its outstanding properties SiC is a semiconductor material of increasing importance for special applications [1]. The implantation of group III ions into single-crystal SiC is the only method to create laterally structured p-doped layers. However, ion implantation always creates radiation damage [2]. Efforts to minimize this damage by heating the substrate during implantation and by post-implantation annealing are of high importance. Up to now there have been no systematical investigations concerning the influence of substrate temperature on the crystal damage state. For example the formation of temperature stable defects could decrease the carrier activation after high temperature annealing. The as-implanted state of a 400 nm thick buried Al-implanted layer with a concentration of $5x10^{19}$ cm^{-3} in epitaxial n-type 6H-SiC has been investigated by Cross section Electron Microscopy (XTEM), RUTHERFORD Backscattering Spectrometry / Channeling (RBS/C), Positron Annihilation Spectroscopy (PAS), RAMAN Scattering Spectrometry and HALL effect measurements. The substrate has been kept at temperatures between room temperature and 1300ϒC during implantation. The XTEM-investigations reveal, that no extended defects appear up to a temperature of 800ϒC. However, after implantation at 1050ϒC dislocation loops within the profile region are seen. This change of defect quality is confirmed by an increase of the dechanneling factor in this temperature region extracted from the RBS/C spectra. The relative damage level obtained by RBS/C decreases with increasing implantation temperature down to 4 % at 800ϒC exhibiting no more significant change up to 1300ϒC. In contrast, the relative damage level from RAMAN measurements given by the normalized intensity of the TO line at 789 nm decreases down to 0.1 at 1200 ϒC with increasing temperature. However, for extended depth measurements to 1600 nm the RAMAN measurements indicate a higher damage level than within the implanted layer. This correlates with PAS analyses detecting a vacancy cluster region beyond the implanted layer. From the viewpoint of electrical HALL-measurernents, only the samples implanted at ⊕1200 ϒC show p-type conduction in the as-implanted state. Regarding the defects the electrical properties of the implanted SiC are in relation to the perturbed bond concentrations detected by RAMAN within the implanted layer. [1] W.J. Choyke, G. Pensl; MRS bulletin 3/1997, p. 25 ff. [2] V. Heera, W. Skorupa; MRS Symp.Proc.Vol.438 (1997), p. 241 ff.

4:50 PM, K10
Late News

Wednesday PM, June 24, 1998

Session L. Structure and Luminescence of III-Nitrides

Room: 203
Location: Physics

Session Chairs: J. S. Speck, University of California, Materials Department, Santa Barbara, CA 93106 USA; K. Doverspike, Cree Research, Durham, NC 27703 USA

1:30 PM, L1*Invited

Compositional, Structural, and Optical Properties of Pseudomorphic InGaN on GaN: L. T. ROMANO[1]; M. D. McCluskey[1]; B. S. Krusor[1]; C. G. Van De Walle[1]; C. P. Master[1]; D. P. Bour[1]; [1]Xerox PARC, 3333 Coyote Hill Road, Palo Alto, CA 94304 USA

The effect of strain and phase separation has been studied on thick and thin layers of $In_xGa_{1-x}N$ alloys grown by MOCVD. The thick (300nm) $In_xGa_{1-x}N$ layers were grown on 2μm thick GaN, on c-plane sapphire substrates. Composition of the overlayers was determined by Rutherford Back-scattering Spectrometry and correlated to both the 'a' and 'c' lattice constants from x-ray diffraction (XRD). They were found to be pseudomorphic with the GaN up to x = 0.12 which is well beyond the critical thickness expected for strain relaxation. An experimentally determined value for Poisson's ratio, v = 0.18, could be obtained from these measurements. Vegard's Law was found to be applicable at these compositions by including the biaxial strain. Optical transmission measurements showed that if strain is included, the band gap has a bowing parameter b = 3.8eV at x = 0.10. Transmission electron microscopy (TEM) studies showed V-groove defects in the $In_xGa_{1-x}N$ overlayers but no indication of phase separation. No additional threading dislocations were observed at the $In_xGa_{1-x}N$/GaN interface, however stacking fault defects were observed. For compositions x > 0. 12, the films were found to be phase separated by XRD at these thicknesses. For thin (<5nm) $In_xGa_{1-x}N$ layers in multiple quantum well (MQW) structures with GaN barriers, compositions up to x = 0.30 could be achieved with no indication of phase separation by XRD or TEM. These layers were also found to be pseudomorphic with the GaN barriers. However annealling these sarnples at times and temperatures beyond those typically used during growth, showed that phase separation is possible in the MQW layers, and is accompanied by void formation.

2:10 PM, L2+

Near Field Spectroscopy of InGaN Single and Multiple Quantum Wells: DARRON KUAN HUA YOUNG[1]; Paul A. Crowell[2]; STACIA KELLER[1]; Micahel Mack[1]; David Awschalom[2]; JIM SPECK[3]; Evelyn Hu[1]; [1]University of California Santa Barbara, Electrical and Computer Engineering, Santa Barbara, CA 93106 USA; [2]UCSB, Physics Dept, Physics, Santa Barbara, CA 93106 USA; [3]UCSB, Materials Dept, Materials Dept, Santa Barbara, CA 93106 USA

The realization of various laser diodes and light emitting diodes based on $In_xGaN_{1-x}GaN$ quantum wells (QWs) has proven that these materials are exceptionally efficient photo emitters in the blue portion of the visible spectrum. On the other hand, the very large threading dislocation densities (10^9 to 10^{10} cm-2) in InGaN epilayers and quantum wells have led to great speculation on the nature of the radiative recombination in these materials. While some photoluminescence (PL) and time resolved PL measurements suggest band to band recombination of free carriers, other measurements allude to excitonic recombination localized by alloy fluctuations, none of these far field experiments have probed with length scales less than one micron. Our experiments use near field spectroscopy, a high resolution non-destructive probe of the local carriers, to examine possible fluctuations in the luminescence of InGaN single quantum and multiple quantum well materials. The samples used were a single MOCVD grown 3 nm InGaN quantum well, as well as 2.5 nm InGaN multiple quantum well samples clad by GaN having 5, 10, 20, 40 quantum wells. The near field apparatus we used had a spatial resolution of ~0.2 microns. For the single QW sample, although spatial fluctuations were observed in the luminescence, we found no spectroscopic signature of the recombination of strongly localized carriers in the single QW at temperatures above 50K. When more than five QWs are grown concurrently, threading dislocations propagate perpendicularly through the sample forming inverted hexagonal defects. Cross-sectional transmission electron microscopy (TEM) has shown, that along the sidewalls of these defects, thicker quantum wells with lower energies are grown concurrently with the normal basal quantum wells. Due to its V like structure, the hexagonal defect grows as the number of quantum wells is increased. The diameters of these defects reach about 400 nm in diameter for a 40 quantum well sample. Our measurements attempt to resolve the energetically lower quantum well luminescence. In the 40QW sample, the main (basal) quantum well luminescence (3.08eV) is the brightest and shows no structure although the intensity is non uniform on sub micron length scales. Spatial maps of the lower energy peaks (3.03 eV and 2.95 eV) show hexagonal structure; their size and density agree with their cross-sectional TEM. We believe this luminescence originates from the sidewalls of the defects. Spectral shifts and their FWHM dependence on temperature will also be discussed.

2:30 PM, L3

Photoluminescence Characteristics and Pit Formation Of InGaN/GaN Quantum-Well Structures Grown on Sapphire Substrates by Low-Pressure Metalorganic Vapor Phase Epitaxy: KENJI UCHIDA[1]; Masahiko Kawata[1]; Tao Yang[1]; Atsuko Niwa[1]; Jun Gotoh[1]; [1]Hitachi Ltd., Central Research Laboratory, 1-280 Higashi-Koigakubo, Kokubunji, Tokyo 185 Japan

High-quality InGaN-based quantum-well (QW) structures and hetero interfaces are of great importance for optoelectronic devices operating in the visible to ultraviolet wavelength region. In this study, we examined the influence of growth interruption time and of QW number on the crystalline quality of InGaN/GaN-QW structures. The QW structures were grown on 1500-nm-thick underlying GaN layers on c-face sapphire substrates by low-pressure metaloraganic vapor phase epitaxy at 735ϒC. The sources were trime thylgallium (TMGa), triethylgallium (TEGa), trimethylindium (TMIn), and ammonia (NH_3) with both H_2 and N_2 carrier gases. The samples were characterized by photoluminescence (PL), atomic force microscopy (AFM), and transmission electron microscopy (TEM). The PL characteristics depends on the growth interruption time and on the number of QWs. The 300 K PL spectra of $In_{0.17}Ga_{0.83}N$ (3 nm) / GaN (5 nm)-single QWs (SQW) grown with different interruption times show significant variation of the peak wavelength, intensity, and line width. While 5 seconds growth interruption produces a strong peak at 394 nm with a FWHM of 53 meV, only weak emission at 378 nm with a FWHM of 115 meV is observed after 20 seconds growth interruption. This difference suggests that significant re-evaporation of In in the InGaN QW occurs during growth interruption by closing the group-III sources. On the basis of these results, we grew multiple-QW structures with an optimum interruption time of 5 seconds. Despite the same flow rates and growth time for each QW layer, the PL spectra for samples with 3 (TQW) and 5 QWs (MQW) shifted to longer wavelengths of 397 nm and 407 nm, respectively. The AFM measurements revealed a high density of hexagonal-shaped pits on the QW surfaces. The pit sizes on the QW surfaces increased dramatically with interruption time. The surfaces of the TQW and MQW samples always showed large pit sizes than SQWs. Cross-sectional TEM observations of the MQW samples revealed an open V-shape of the pits, and the pit bottoms connect with threading dislocations. We found that both, InGaN well and GaN barrier layers grown on (0001) plane became thick with increasing number of the QWs. The growth rate variation of the InGaN well layers was higher than that of the GaN barrier layers. Therefore, the observed PL characteristics for the QW structures are explained in terms of compositional change of In in the InGaN well layers due to the open hexagonally shaped pit formation.

2:50 PM, L4

Direct Imaging of In-rich Nanoclusters in InGaN, Correlating Highly Spatially Resolved Cathodoluminescence Microscopy, Transmission Electron Microscopy and Micro-Raman Spectroscopy: FRANK BERTRAM[1]; J. Christen[1]; A. Hoffmann[2]; S. Selke[3]; S. Einfeldt[3]; D. Hommel[3]; [1]Otto-Von-Guericke University, Institute of Exp. Physics, PO Box 4210, Solid State Physics, Magdeburg, Sachsen-Anhalt 39016 Germany; [2]Technical University Berlin, Exp. Physics, Solid State Physics, Berlin Germany; [3]University of Bremen, Exp. Physics, Solid State Physics, Bremen Germany

InGaN is the most prominent candidate for the active region of blue light emitting diodes and in particular laser diodes. Severe problems arise from the fact, that InGaN is neither lattice matched to any common substrate, nor to the GaN confinement layers involved in such a device. A complex crystalline nanostructure of inhomogene chemical composition arises in the ternary InGaN epilayers. This creates a strong spatial localization of the electrons, holes, and excitons. Even if this localization isn't strong enough for quantum confinement (i.e., no In rich Quantum Dots are formed), a strong impact on the recombination kinetics is expected as the localized carriers are protected from non-radiative recombination centers (defects, dislocations, ...). A detailed microscopical characterization yielding a correlation of the structural, chemical and optical properties on a nanometer scale is essential for a physical understanding of the fundamental recombination processes. Here we present comprehensive investigation by highly spatially resolved (lateral resolution < 50nm) and time resolved cathodoluminescence microscopy (CL), micro-Raman Spectroscopy (μ-Raman) in correlation with analytical and high-resolution transmission electron microscopy (TEM), energy-dispersive X-ray microanalysis (EDX) and atomic force microscopy (AFM). The sample under study is a 1μm thick InGaN-epilayer with an average In-content of [In]average = 4.5%, grown by MBE on basal plane sapphire using a 30nm thick GaN buffer. Plan view and cross sectional mappings of the local CL emission wavelength directly visualize lateral and vertical inhomogeneities in the chemical composition of InGaN. Beside an overall vertical In-gradient ([In] decreases in c-direction) and an In accumulation close to the surface, local In rich nano-clusters showing a columnar structure in growth direction are observed. These results quantitatively agree with mappings of In to Ga ratio obtained by EDX in TEM. The overall In concentration decreases slowly in growth direction, but there is a thin In rich surface layer. The lateral variations in In concentration are irregular and more pronounced. Vertical columnar domains of high local In-content up to [In] = 30% are identified. While the laterally averaged CL luminescence shows on very broad band (FWHM = 380meV), local spot mode CL consists of narrow peaks (FWHM < 60meV), showing a strong variation of peak position. A statistical analysis yields no simple mono-modal distribution function but proves a clear preference for discrete CL wavelength, i.e. preference for certain discrete In-concentrations. Time resolved cathodoluminescence visualizes the thermalization of the excess carriers laterally into the nano-domains of lowest bandgap, i.e. highest In-content. The surface morphology is imaged by showing the cluster structure with typical sizes of 200nm in quantitative agreement with the CL- and EDX-microscopy. μ-Raman measurements were carried out with a lateral spatial resolution better than 1μm mapping the local modulation in strain and local free carrier concentration.

3:10 PM Break

3:30 PM, L5+

III-N:Er Materials Doped During Growth by Chemical Beam Epitaxy: J. DEVIN MACKENZIE[1]; Cammy R. Abernathy[1]; Stephen J. Pearton[1]; Uwe Hommerich[2]; John M. Zavada[3]; [1]University of Florida, Materials Science and Engineering, 121 Rhines Hall, Gainesville, FL 32611 USA; [2]Hampton University, Physics, Research Center for Optical Physics, Hampton, VA USA; [3]U.S. Army Research Office, Research Triangle Park, NC USA

1.54 micron Er^{3+} luminescence in III-nitrides has been studied with the intention of understanding the incorporation and behavior of Er^{3+} in the nitrides and evaluating the potential for III-N:Er optoelectronics. Special focus has been placed on developing GaN:Er for incorporation in device structures grown on Si and c-plane Al_2O_3. III-N:Er materials doped during UHV growth from metalorganic and elemental beams have been found to produce AlGaInN:Er films on Al_2O_3, GaAs and Si substrates with intense, room-temperature 1.54 micron photoluminescence which is dependent on impurity concentration, alloy composition, structural quality and doping level. For the first time, strong Er^{3+}-related luminescence was measured at room temperature for GaN:Er doped during growth on c-plane Al_2O_3 and Si. Variation of the C and O background levels through substitution of the Group III source indicates that the presence of these impurities dramatically enhances Er photoluminescence in GaN. GaN films doped with Er to a concentration of 3 x 10^{18} cm^{-3} with [O] ~ 10^{20} cm^{-3} and [C] ~10^{21} cm^{-3} luminesce at 1.54 micron with an intensity more than 2 orders of magnitude greater than films with oxygen and carbon backgrounds of less than 10^{19} cm^{-3}. Increasing the In content in InAlN:Er indicated a maximum in Er activation at an intermediate composition related to the onset of n-type conductivity and/or bandgap narrowing with increasing In fraction. Though concentration quenching was not observed for AlN:Er, a saturation in photoluminescence intensity was observed for [Er] > 10^{18} cm^{-3} in AlN. Developments in basic device structures, such as a GaN:Er/Si Schottky and GaN:Er p/n junction diodes will also be discussed.

3:50 PM, L6

Radiative Efficiency of High Quality Gallium Nitride Thin Films: Peter Mitev[1]; B. Gaffey[1]; M. Gherasimova[1]; L. J. GUIDO[1]; [1]Yale University, Center for Microelectronic Materials and Structures, P.O. Box 208284, New Haven, CT 06520-8284 USA

The external quantum efficiency of group III nitride LEDs can be as high as 2%, despite having threading dislocation densities well in excess of 10^8 cm^{-2}. This observation suggests the radiative efficiency of nitride materials may be much larger than for conventional III-V semiconductors. We report here on measurements of radiative efficiency for high-quality GaN epitaxial layers doped with silicon donors and arsenic isovalent atoms. Four samples were prepared by OMVPE with “equilibrium” electron densities ranging over two orders of magnitude: two silicon-doped samples with n_{eq} = 2 x 10^{17} cm^{-3} and 4 x 10^{18} cm^{-3}; one arsenic-doped sample with n_{eq} = 3 x 10^{17} cm^{-3}; and one nominally undoped sample with n_{eq} = 3 x 10^{16} cm^{-3}. Photoluminescence spectra were recorded over a wide energy range using a “dispersion-free” optical collection set-up. Steady-state excitation was provided by the 351 nm line of an argon-ion laser with the incident intensity varied from 0.01 to 250 W/cm^2 to investigate radiative recombination in both the small-signal and large-signal regimes. The absolute collection efficiency of the experimental set-up was calibrated using an optical diffuser. The external quantum efficiency was obtained by normalizing the band-edge integrated intensity by the product of collection efficiency x absorbed laser intensity. The radiative efficiency was derived from the external

quantum efficiency by correcting for both self-absorption and total internal reflection. The measured radiative efficiency, η_{rad}, approaches 100% at 4.5 K for both silicon-doped samples. In contrast, η_{rad} is only 25% for the undoped case and is 3x smaller yet for the arsenic-doped sample. At T = 300 K, the radiative efficiency increases linearly with electron density at low doping levels; that is, η_{rad}(silicon) = 0.0033 and η_{rad}(undoped) = 0.0005, which yields a ratio of 6.67. However, for the most heavily-doped sample, η_{rad} saturates at 1.2% even though n_{eq} increases by a factor of 133x relative to the undoped case. This sublinear behaviour of η_{rad}(300K) at high silicon doping happens because yellow-band emission begins to dominate the luminscence spectrum. The radiative efficiency for the arsenic-doped sample decreases from 8% at 4.5 K to 1% at 300 K. This eight-fold decrease compares favorably with the precipitous drop exhibited by the two silicon-doped samples. Our experimental findings demonstrate that the radiative efficiency of GaN at 4.5 K is not necessarily 100% even for high-quality samples. In addition, the data reported here indicate that radiative recombination via the "yellow-band" presents an upper limit to the radiative efficiency of GaN at 300 K. This yellow band contribution increases with silicon doping, but can be reduced significantly by counter-doping with arsenic.

4:10 PM, L7

Influence of Hydrogenation and Dehydrogenation on Yellow Luminescence of GaN Films Grown by Halide Vapor Phase Epitaxy with C-Doping and H2 Addition into the Growth Ambient: RONG ZHANG[1]; Ling Zhang[1]; Thomas F. Kuech[1]; [1]University of Wisconsin, Department of Chemical Engineering, 1415 Engineering Drive, Madison, WI 53706 USA

Photoluminescence (PL) properties of GaN films grown by halide vapor phase epitaxy with C-doping or H_2 addition into the growth ambient have been systematically investigated. The hydrogen induced yellow luminescence (YL) (~2.2-2.3eV) can be passivated by a high-temperature hydrogenation with the ratio of the integrated intensity of the YL band to that of the bandedge (BE) band changed from 6.8 to 0.065. This deactivation of the yellow luminescence is partially reversible. The low-energy component of this luminescence band can be effectively reactivated by a high-temperature N_2 annealing with the ratio mentioned above changed to 2.9, while the high-energy component of the YL band can not be recovered under the same condition. The reactivated part of the YL band can be passivated again by another hydrogenation process. Only the low-energy part of the YL band induced by the C-doping can be quenched by the hydrogenation and then be regenerated by the N_2 annealing. In both cases, the high-temperature N_2 annealing changes the PL properties only a little. The hydrogen passivation effects on both carbon and hydrogen induced YL have been explained by the formation of the neutral donor-hydrogen acceptor (D^+-H^-) complex in the GaN films. This neutral complex is either non-optically-active or has a different emission energy from the 'yellow band'. The dissociation of that neutral complex during the high-temperature N_2 annealing can revive the low-energy 'yellow band'. A new PL line has been found in the C-doped (3.42eV) and 'H_2-growth' (3.43eV) GaN after the hydrogenation. The new line in the 'H_2-growth' GaN can be diminished by the high-temperature N_2 annealing and then reactivated by another hydrogen passivation process, indicating that this line is related to (D^+-H^-) complex in the material. The line at 3.42eV in the C-doped GaN has no significant change after the dehydrogenation.

4:30 PM, L8+

Detection of Free-To-Bound Transitions by Photoluminescence Excitation: E. E. REUTER[1]; S. J. Rhee[1]; S. Kim[1]; S. G. Bishop[1]; R. J. Molnar[2]; [1]University of Illinois at Urbana, Department of Electrical and Computer Engineering, 127 Microelectronics Lab MC-249, 208 N. Wright St., Urbana, IL 61801 USA; [2]Massachusetts Institute of Technology, Lincoln Laboratory, 244 Wood St., Lexington, MA 02173 USA

The technological importance of GaN as the basis for a broad range of light emitting devices and high temperature, high power electronic devices has motivated intensive investigation of shallow donor and acceptor impurity or defect levels in this material. In this paper, it is demonstrated that photoluminescence excitation (PLE) spectroscopy is a powerful tool for the detection of shallow donors and acceptors on the basis of near-band gap optical absorption by free-to-bound transitions. In particular, PLE provides conclusive evidence for the presence in undoped HVPE GaN of an acceptor or donor level with ~120 meV binding energy. Previous photoluminescence (PL) studies[1-3] of undoped layers of epitaxial wurtzite GaN have detected a characteristic PL band at about 3.40 eV that has been interpreted variously as a donor free-to-bound transition (D0h), an acceptor free-to-bound transition (A0e), or an LOphonon replica of the A free exciton. We have performed temperature dependent photoluminescence excitation (PLE) spectroscopy of the well-known yellow luminescence (YL) band in undoped wurtzite GaN grown by hydride vapor phase epitaxy (HVPE) on sapphire. At a temperature of 150K we have observed a sharp onset or threshold at about ~120 meV below the GaN bandgap in the extrinsic (below-gap) PLE spectrum. At temperatures below 150K, the yellow band PLE exhibits no onset at 120meV, suggesting that the onset is due to a free-to-bound transition involving an unidentified donor or acceptor level with a binding energy of 120 meV. This 120 meV onset corresponds closely with the energy of the ~3.40 eV PL band. The ~120 meV binding energy determined from the PLE onset is consistent with the 116 meV binding energy derived[1,2]from the uinidentified PL peak. At temperatures above 300K, these PLE spectra exhibit an additional onset at 204 +/- 20 meV below the band gap. This onset corresponds closely with the well-known ~3.28 eV PL band which is attributed to donor-acceptor-pair (DAP) or acceptor free-to-bound transitions[4,5],thereby providing another example of the effectiveness of PLE in detecting absorption due to shallow levels in GaN. * Supported by DARPA (MDA 972-94-1-0004) and the Joint Services Electronics Program. [1] U. Kaufmann et al., Mat. Res. Soc. Symp. Vol. 395, 633 (1996). [2] C. Merz et al., Mats. Sci. and Eng. B43, 176 (1997). [3] B. Skromme et al., Mat. Res. Soc. Symp. Vol. 449, 713 (1997). [4] R. Dingle and M. Ilegems, Solid State Comm., Vol. 9, 175-180 (1971). [5] S. Fischer et al., Appl. Phys. Lett., Vol. 67 (9), 1298-1300 (1995).

4:50 PM, L9

Infra-Red Spectroscopy of Hexagonal GaN/AlN Short-Period Superlattices: ALEXANDER MINTAIROV[1]; Sylvain Raimond[1]; James Merz[1]; Andrei Osinsky[2]; Ramis Gaska[2]; [1]Notre Dame University, Electrical Engineering, EE Department, Notre Dame, IN 46556 USA; [2]APA Optics, 2950 N.E. 84th Lane, Blane, Minnesota 55434 USA

Wurtzite type GaN/AlN heterostructures are of great current interest due to their applications for wide band-gap optoelectronics. In the present work we report the first IR-reflectance spectroscopy measurements of the optical phonon mode frequencies of GaN/AlN short-period superlattices (SLs) grown on sapphire substrates. The GaNn/AlNm (n=1-8, m=1, 3, 6) SLs were grown by switched atomic layer metalorganic chemical vapour deposition [1]. In the 400-1000 cm^{-1} frequency range we observed several restsrahl bands, similar to those previously reported [2]. The bands appeared at ~500-600 cm^{-1}, which we attribute to GaN-type modes, and reveal additional fine structure having a strong dependence on the number of SL periods. We observed a high frequency shift of the AlN-type band (at ~800 cm^{-1}) with increasing angle of incidence and with an increase in the number of SL periods. Using a model including two anisotropic layers (SL+buffer) on an anisotropic semi-infinite substrate, and a multi-mode representation of the SL dielectric function, we reproduced the experimentally-observed features of the IR reflectance spectra in our calculations. This gives the A1(LOp) and E1(TOp) SL mode frequencies. Up to eight SL polar optic modes have been identified in the IR spectra of the highest period SL (n=6, m=8). The observed behavior of the SL modes qualitively agrees with strong directional and spatial dispersion of the AlN and with a dispersionless character of the GaN bulk polar optic phonons. Lattice dynamical calculations of the phonon-dispersion curves of the hexagonal GaN(n)/AlN(m) SL are in progress. 1. M. Asif Khan, J.N. Kuzina, D.T. Olson, T. George and W.T. Pike , Appl. Phys. Lett. 63, 3470 (1993)2. 2M.F. MacMillan, R.P. Devaty, W.J. Choyke, M. Asif Khan and J.N. Kuzina, J. Appl. Phys. 80, 2372 1996.

THURSDAY AM

June 25, 1998

Session M. Special Topical Session on: New Frontiers in Spontaneous Ordering in Semiconductor Alloys

Room: E303
Location: Thornton Hall

Session Chairs: Alex Zunger, NREL, Golden, CO 80401; Ted Moustakas, Boston University, Dept. of Physics, Boston MA 02215 USA

8:20 AM, M1*Invited

The Influence of Ordering on the Absorption, Electroabsorption and Electroluminescence Of GaInP and Potential Device Applications: P. KIESEL[1]; T. Kippenberg[1]; J. Krauss[1]; E. Greger[2]; M. Moser[2]; G. H. Dohler[2]; [1]University of Eriangen, Institut fuer Technische Physik, Erwin-Rommel-Str.1, Erlangen D-91058 Germany; [2]CSEM, Badenerstra D-569, Zurich Ch-8048 Switzerland

Under suitable growth conditions GaInP epitaxial layers, lattice matched to GaAs, show a pronounced spontaneous self ordering of the CuPt-type [1]. For growth in the [100]-direction this ordering results in alternating Ga-rich and In-rich planes along two of the four [111] crystal directions. The mono-atomic superlattice causes significant changes of the electronic structure compared to the normal disordered alloy. In particular, ordered crystals exhibit a band gap reduction of up to about 100 meV and a significant valence band splitting at the G-point. As a consequence a strong polarization dependence of the optical transition probabilities with regard to the ordering directions results. For instance, optical transitions between the highest valence band and the conduction band become forbidden for light polarized parallel to the ordering direction. Even for light propagating normal to the (100)-oriented crystal surface the polarization anisotropy is strongly pronounced. In this talk we will demonstrate how this polarization anisotropy can be used for both fundamental investigations of the electronic structure of ordered material [2] as well as for various electro-optical devices [3-6]. We have studied the polarization dependence of the absorption, electro-absorption (Franz-Keldysh- effect) and electroluminescence of (AlxGa1-x)0.5In0.5P double hetero p-i-n structures with intrinsic layers consisting of ordered material. An ordering induced shift of the Franz-Keldysh spectra of up to 12 meV has been observed between the electro-absorption spectra for light polarized parallel to the [011] and [01-1] crystal direction, respectively. A deconvolution of the contributions of the two upper valence bands, based on simple considerations of the valence band wave functions and the angular dependence of the dipole matrix elements, turns out to be possible. In this way we have been able do deduce the valence band splitting as a function of the ordering parameter. Additional experiments with [011] and[01-1] in-plane electric fields have corroborated the validity of our analysis and, in addition, have allowed an accurate determination of the position of the spin split-off valence band. The relation between band gap reduction, valence band splitting, position of the split-off band and ordering parameter h, deduced from these experiments, agrees almost perfectly with the theory by Wei and Zunger [7]. We will also report on some device oriented work. In our studies of the electroluminescence emitted from double hetero p-i-n LEDs with ordered GaInP as active layer we have observed pronounced polarization effects. Depending on the ordering parameter h, the room temperature electroluminescence exhibits a contrast ratio of up to 2dB (for h =0.37) between the [011] and [01-1] polarized part of the emitted light.Very recently we have also demonstrated a polarization sensitive threshold switch with a high photo-conductive gain. The electrical output of the device can be changed by many orders of magnitude as a function of the polarization angle of the incident light. A switching contrast of almost 50 dB and a maximum sensitivity of about 3 dB/degree have been demonstrated. [1] A. Gomyo, T. Suzuki, K. Kobayashi, I. Hino, T. Yussa, Appl. Phys. Lett. 50, 673 (1987). [2] P. Kiesel, T. Kippenberg, E. Greger, M. Moser, U. Hilburger, G. Schmiedel, and G.H. Döhler, accepted for publication in Physica B (Proceedings of MSS8). [3] E. Greger, K.H. Gulden, P. Riel, H.P. Schweizer, M. Moser, G. Schmiedel, P. Kiesel, and G.H. Döhler, Appl. Phys. Lett. 68, 2383 (1996). [4] G. Schmiedel, P. Kiesel, G.H. Döhler, E. Greger, K.H. Gulden, H.P. Schweitzer, and M. Moser, J. Appl. Phys. 81, 1008 (1997). [5] E. Greger, K.H. Gulden, M. Moser, G. Schmiedel, P. Kiesel, and G.H. Döhler, Appl. Phys. Lett. 70, 1459-1461 (1997). [6] E. Greger, K.H. Gulden, P. Riel, M. Moser, T. Kippenberg, P. Kiesel, and G.H. Döhler, Appl. Phys. Lett. (Dec 1997). [7] S.-H. Wei and A. Zunger, Phys. Rev. B 39, 3279 (1989).

8:40 AM, M2*Invited

Observations of Ordering-Induced Indirect to Direct Transition in AlGaInP: T. KITA[1]; K. Yamashita[1]; T. Nishino[1]; [1]Kobe University, Department of Electrical and Electronics Engineering, Faculty of Engineering, Rokkodai 1-1, Nada, Kobe 657 Japan

We have investigated ordering-induced direct optical transitions in indirect gap (AlxGa1-x)0.5 In0.5P. There has been a strong interest in indirect-gap semiconductors for their application to light emitting devices. However, an extremely low efficiency of light emission prevents the indirect-gap semiconductors from application to their optoelectronic devices. To obtain a strong emission from an indirect-gap semiconductors, we focus our attention on the band-structure engineering using monolayer superlattices of long-range ordered alloy semiconductors. (AlxGa1-x)0.5 In0.5P alloy are well known to form atomically ordered phases when they are grown by vapor-phase epitaxy on a lattice matched GaAs (001) substrate. This ordering has a periodic alternation of the column-III sublattice plane along the [11] and [11]. All forms of deviations from perfect randomness affect profoundly the material properties especially for the electronic band structure. Because of the reduction of the crystal symmetry, the band structure in the zinc-blende Brillouin zone folds into the reduced superlattice-Brillouin zone. In particular, the fundamental band gap at the G point is reduced by band-folding effects. The direct band gap of (AlxGa1-x)0.5 In0.5P random alloy is changed by the Al-mole fraction from 2.1 eV to 2.6 eV. When the Al-mole fraction is larger than about 0.4, the transition type becomes indirect, and the conduction-band minimum is at the X valley. Since the magnitude of the symmetry-enforced changes in the band structure is a function of order parameter, a tuning of the G-level energy by the atomic ordering can produce a direct transition. From photoluminescence and electroreflectance measurements on ordered (AlxGa1-x)0.5 In0.5P, we found that the G 6c level crosses the X 6c level as the band-gap is reduced. The photoluminescence-decay profile and a temperature dependence of the photoluminescence intensity indicate that the strongly ordered (AlxGa1-x)0.5 In0.5P is optically direct. Furthermore, the low temperature luminescence of the ordered (AlxGa1-x)0.5 In0.5P shows strong carrier localization effects in the fluctuated band structure which plays a key role in the luminescence intensity.

9:00 AM, M3*Invited

Ordering in GaInP/AlGaInP Epitaxial Structures: F. SCHOLZ[1]; C. Geng[2]; P. Ernst[3]; M. Burkhard[4]; H. Schweizer[5]; R. Wirth[5]; A. Moritz[5]; A. Hangleiter[6]; A. Muhe[6]; F. Phillipp[7]; [1]Universitat Stuttgart, 4. Physikalisches Institut, Stuttgart D-70550 Germany; [2]TEMIC, Heilbronn Germany; [3]Robert Bosch Gmbh, Reutlingen Germany; [4]Uniphase, Ruschlikon Switzerland; [5]Robert Bosch GmbH, Schwieberdingen Germany; [6]Universitat Erlangen Germany

As many other ternary and quaternary compound semiconductors, GaInP epitaxial layers show natural superlattice ordering consisting of Ga-rich and In-rich (111) crystal planes, when grown under specific growth conditions. The major factor controlling the degree of ordering is the growth temperature. Strongest ordering is observed at temperatures around 670°C, whereas both, lower and higher temperatures result in less pronounced ordering. Additionally, parameters as the growth rate, V-III ratio, substrate misorientation or doping may influence the ordering. Transmission electron microscopy studies have revealed that domains are formed differing by either the ordering direction or a phase shift of the InP-GaP superlattice. In the recent years, we have studied the development of ordering in GaInP/AlGaInP hetero structures grown by low pressure metalorganic vapor phase epitaxy (MOVPE) and its consequences on basic material and device properties. We found that the domain size increased monotonously with the growth temperature. Therefore, strongly ordered layers normally show a high density of domain boundaries which give rise to a “moving emission peak” in photoluminescence (PL) [1]. Large domains, on the

other hand, can only be found in less ordered material grown at higher temperature. As ordering breaks the crystal symmetry, it influences strongly the band structure. Although the ordering induced band gap reduction is the most evident feature, it is less suited to evaluate quantitatively the degree of ordering. Another consequence is the lifting of the valence band degeneracy, similar as in strained material or quantum wells. Thus, by measuring the valence band splitting, the degree of ordering could be quantitatively deduced [2]. The lower joint density of states owing to the split valence band is expected to be favorable for laser devices. However, this advantage normally is overcompensated by the high density of domain boundaries in strongly ordered material. By employing a "two-temperature-step" growth process, we could realize large size strongly ordered domains in the active region of a GaInP laser structure which indeed showed higher optical gain and lower threshold currents [3]. Moreover, the ordering influences the polarization properties of optical waveguides. We have shown that this may be used in polarization switching devices [4]. Finally, ordering may be locally destroyed by, e.g., ion implantation resulting in a lateral modulation of the band gap. This technique has been used to fabricate an optically pumped distributed feed-back laser without the otherwise needed etching of a grating [5]. In our contribution, we like to review our recent investigations on these topics and discuss the relevance of ordering for basic studies and device applications. [1] P. Ernst, C. Geng, G. Hahn, F. Scholz, H. Schweizer, F. Phillipp, A. Mascarenhas, J. Appl. Phys. 79 (1996) 2633. [2] P. Ernst, C. Geng, F. Scholz, H. Schweizer, Y. Zhang, A. Mascarenhas, Appl. Phys. Lett. 67 (1995) 2347. [3] C. Geng, A. Moritz, S. Heppel, A. Mühe, J. Kuhn, P. Ernst, H. Schweizer, F. Phillipp, A. Hangleiter, F. Scholz, J. Crystal Growth 170 (1997) 418. [4] R. Wirth, A. Moritz, C. Geng, F. Scholz, A. Hangleiter, Appl. Phys. Lett. 69 (1996) 2225. [5] F. Scholz, C. Geng, M. Burkard, H.-P. Gauggel, H. Schweizer, R. Wirth, A. Moritz, A. Hangleiter; Proc. 8th Int. Conf. on Modulated Semiconductors, Santa Barbara, USA, July 1997 (to be published).

9:20 AM, M4*Invited

Measurements of the Order Parameter in $GaInP_2$ Using Nuclear Magnetic Resonance: P. C. TAYLOR[1]; [1]University of Utah, Department of Physics, 115 S 1400 E, RM 201, Salt Lake City, UT 84112-0830 USA

Many ternary III-V semiconductors exhibit a propensity for the two elements on the common sublattice to order [1]. In spite of the fact that partial ordering is common, it has proved difficult to obtain reliable estimates of the degree of ordering. Since in the perfectly ordered structure there exist lattice planes that contain only one of the two elements of the common sublattice, one can define the order parameter, h (0 £ h £ 1), as the fractional filling of such a plane by the appropriate element. Most estimates of h come from fitting experimentally determined optical properties to theoretically calculated trends as functions of the order parameter. One can employ nuclear magnetic resonance (NMR) techniques to obtain estimates of h on a local scale that do not depend on calculations of the band structure, but rather depend on calculations of the local structural order [2]. Using the prototypical system, GaInP2, and measurements of 69Ga, 71Ga, and 115In NMR, one can obtain estimates of h. Roughly speaking, these estimates rely on the fact that the NMR, which measures the gradient of the electric field at the In or Ga nuclear sites, is very sensitive to the local symmetry. In perfectly ordered GaInP2 there exists a symmetry axis along the [111] ordering direction while in GaInP2 where the Ga and In are placed randomly on the cation sublattice (so-called, disordered GaInP2) the local symmetry is most often along one of the six, equally-probable [001] directions. These two different local symmetries can be detected by measuring the NMR as a function of the orientation of the magnetic field with respect to the crystal axes. The details of this procedure will be discussed, and comparisons with calculations [2,3,4] will be presented. [1] A. Zunger and S. Mahajan, in Handbook of Semiconductors, 2nd ed., edited by S. Mahajan, vol. 3 (Elsivier, Amsterdam, 1994) p. 1339. [2] D. Mao, P.C. Taylor, S.R. Kurtz, M.C. Wu, and W.A. Harrison, Phys. Rev. Lett. 76, 4769 (1996). [3] S.H. Wei and A. Zunger, J. Chem. Phys. 107, 1931 (1997). [4] C. Nelson, P.C. Taylor and W.A. Harrison, unpublished.

9:40 AM, M5*Invited

Vibrational Properties of Spontaneously-Ordered $GaInP_2$: H. M. CHEONG[1]; A. Mascarenhas[1]; F. Alsina[1]; B. Fluegel[1]; Y. Zhang[1]; J. M. Olson[1]; [1]National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401 USA

GaInP2 alloys grown by MOCVD on (001) GaAs substrates exhibit a spontaneous CuPt-type ordering of various degrees along the [11] or [11] directions, depending on the growth conditions and the substrate misorientation. Theses structures resemble monolayer superlattices of Ga(0.5+h)In(0.5-h)P/Ga(0.5-h)In(0.5+h)P (0£h£1) along the ordering direction. Due to this ordering, the symmetry of the crystal changes from the Td symmetry of zinc-blende to trigonal C3v symmetry. The electronic, optical, and lattice-dynamical properties of the ordered alloy should reflect this change in symmetry. So far, several symmetry-induced phenomena, including valence-band splitting, birefringence, pyroelectricity, and extra phonon modes, have been observed and found to be consistent with the C3v symmetry of the ordered crystal. In Raman scattering measurements taken from the (001) growth surface, three extra phonon peaks at 60, 205, and 354 cm-1 have been observed for ordered GaInP2 samples. The two lower-frequency modes at 60 and 205 cm-1 are identified as due to the 'zone-folded' transverse and longitudinal acoustic phonon branches, respectively, and the extra mode at 354 cm-1 as due to a logitudinal mode. The nature of these extra peaks were investigated using far-infrared reflection and transmission measurements and micro-Raman scattering measurements in the (10) and (11) backscattering geometries, and in the right-angle scattering geometry between the (001) and (10) surfaces. In addition, resonance Raman scattering measurements on the (001) growth surface show a pronounced resonance near the fundamental band gap of the ordered material. This result will be interpreted in terms of the electronic structure and the phonon properties of the ordered alloys.

10:00 AM, M6*Invited

Observation of Ordering-Induced Electric Fields in $GaInP_2$ by Scanning Capacitance and Near-Field Optical Microscopy: C. C. WILLIAMS[1]; [1]University of Utah, Department of Physics, Salt Lake City, UT 84112 USA

Dramatic differences between the local electronic properties of single and two-variant GaInP have been observed by Scanning Capacitance Microscopy (SCM) and Near-field Scanning Optical Microscopy (NSOM) [1,2]. In single-variant GaInP, spatially uniform SCM and NSOM signals are observed. In two-variant GaInP, the SCM and NSOM signals vary strongly on the scale of the variant size. Additionally, both n- and p-type like behavior is observed by SCM on samples with nominally uniform doping. Imaging of the same sample area by SCM and NSOM has demonstrated that the photoluminescence (PL) comes only from small isolated domains which are n-type like in nominally n-type doped two-variant GaInP. A model has been proposed to explain these results. The proposal is that internal electric fields are present in two-variant samples which cause local band bending and induce the n- and p-type behavior [2]. This same model also correctly predicts the non-uniform PL intensity observed by NSOM. One dimensional modeling of the internal fields has been performed and compared with the measured results. The comparison indicates that the magnitude of the unscreened internal field is approximately 1mV/A. This value is consistent with the predictions of Froyen [3]. [1] J-K. Leong, C.C. Williams, J.M. Olson, S. Froyen, Appl. Phys. Lett. 69, 4081 (1996). [2] J-K. Leong. C.C. Williams, J.M. Olson, Phys. Rev. B 56, 1472 (1997). [3] S. Froyen, A. Zunger, and A. Mascarenhas, Appl. Phys. Lett. 68, 2852 (1996).

10:20 AM, M7*Invited

Theory of Fingerprints of Ordering: S. H. WEI[1]; [1]National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401 USA

Many III-V AxB1-xC semiconductor alloys exhibit spontaneous CuPt ordering when grown from the vapor phase. The ordered phase consists of alternate cation monolayer planes Ax+h /2B1-x-h /2 and Ax-h /2B1-x+h /2 stacked along the [111] (or equivalent) directions, where 0£h£1 is the long range order (LRO) parameter. When the zinc-blende disordered alloy forms the ordered CuPt phase, the unit cell is doubled, the Brillouin zone is reduced by half, and the point-group symmetry is changed from Td to C3v. These lead to a series of changes in material properties of the alloy, including (i) new X-ray structure factors that appear at {GZB} + (°, °, °), where {GZB} are zinc-blende reciprocal lattice vectors, (ii) a reduction in the band gap Eg, (iii) a valence band splitting DE12 at the valence band maximum (VBM), (iv) an increase of spin-orbit splitting DSO, (v) polarization dependence of optical transition intensities, (vi) enhancement of the degree of spin polarization of photoelectrons emitted from the VBM, (vii) modified NMR chemical shifts, (viii) anisotropy of effective masses, (ix) reduced direct gap pressure deformation potentials, (x) new optical transition of high-energy folded-in states, and (xi) new phonon modes. We have studied these ordering induced changes using first principles band structure method. We provide a general theory for describing these changes as a function of the degree h of LRO. Specific, experimentally testable predictions are presented. + In

collaboration with A. Zunger, A. Franceschetti and V. Ozolins. * Work is supported by U.S. DOE, contract No. DE-AC02-83-CH10093.

10:40 AM, M8*Invited

Spontaneous Highly-Periodic Compositional Modulation in II-VI Semiconductor Alloys: J. K. FURDYNA[1]; [1]University of Notre Dame, Department of Physics, Notre Dame, IN 46556 USA

We discuss the spontaneous occurrence of highly periodic compositional modulation observed in MBE growth of ternary and quaternary II-VI alloys. The most striking manifestation of this phenomenon observed so far[1] has been in ZnSe(1-x)Te(x) grown on vicinal (100) GaAs substrates, for tilt angles of ca. 4 degrees toward the [111] direction. The period of such spontaneously-formed superlattices is extremely regular, with typical values between 1.5 and 4.0 nm, and is long-range in character. X-ray diffraction studies of such superlattices indicate that the composition x varies sinusoidally, typically between the values of 0.25 and 0.75. We will discuss the MBE growth parameters under which such compositional modulation is observed in II-VI alloys; our current understanding of the mechanisms that drive this self-organized phenomenon; detailed structural properties of spontaneous ZnSe(1-x)Te(x) superlattices; and preliminary optical data obtained on these systems. So far such regular spontaneous modulation of composition has only been observed in II-VI systems with two different anions [i.e., in ZnSe(1-x)Te(x), but not in Zn(1-x)Cd(x)Se grown under similar conditions]. It is therefore noteworthy that we have also obtained preliminary but clear indications of similar spontaneous compositional modulation in GaAs(1-x)Sb(x), which—from the point of view of bond and strain geometry—is an exact III-V analogue of the ZnSe(1-x)Te(x) system discussed here. This work supported by Department of Energy Grant DE-FG02-97ER45644. [1] S.P. Ahrenkiel, et. al., Phys. Rev. Letters 75, 2586 (1995).

11:00 AM, M9*Invited

Long Range Order in $Al_xGa_{1-x}N$ Films Grown by Molecular Beam Epitaxy: KARL LUDWIG[1]; K. F. Ludwig, Jr.[2]; T. D. Moustakas[2]; [1]Boston University, Dept. of Physics, 590 Commonwealth Ave., Boston, MA 02215 USA; [2]Boston University, Dept. of Physics and Electrical and Computer Science, Boston, MA 02215 USA

Long-range ordering is observed by x-ray diffraction in AlxGa1-xN thin films grown by electron cyclotron resonance molecular beam epitaxy on sapphire and 6H-SiC substrates. The (0001), (0003) and (0005) x-ray superlattice peaks are largest for Al contents in the 30-50% range, in qualitative agreement with expectations for an ordered structure of ideal Al0.5Ga0.5N stoichiometry with a doubling of the c-axis lattice constant. The average size of ordered domains is typically about 170 nm. The degree of ordering depends on the III/V flux ratio and weakly on Si doping. The effect of annealing on the atomic ordering will be discussed. This work was supported by the BU Photonics Center and DARPA (972-96-3-0014).

11:20 AM, M10*Invited

Epitaxial Growth and Properties of $GaAs_{1-x}N_x$/GaAs: H. TEMKLIN[1]; [1]Texas Tech Univeristy, Electrical Engineering Department, Lubbock, TX 79409 USA

Ternary solid solutions of mixed-anion nitrides, GaAs-GaN, show unusually large bowing coefficients which result in anomalous bandgap dependence on composition. The microscopic crystal structure of these materials is expected to be strongly affected by large size and chemical differences between As and N. The influence of growth conditions and composition on the short and long range ordering, phase separation, and thermodynamic stability is only now beginning to be explored. We report on the growth of high quality GaAs1-xNx on (100) oriented GaAs by metalorganic molecular beam epitaxy. Active nitrogen flux was generated either by a microwave plasma source or decomposition of dimethylhydrazine on the surface of the substrate. Epitaxial growth was carried out at temperatures between 400 and 500oC. The growth rate was in the range of 0.6 -1.0 μm/hr, dependent predominantly on the Ga flux. Incorporation of nitrogen was well behaved and single phase samples with the nitrogen fraction of at least x=0.10 could be grown, provided a critical As4/N flux ratio was exceeded. The layers of GaAs1-xNx were evaluated by double crystal and powder X-ray diffraction (XDR), secondary ion mass spectroscopy (SIMS), photoluminescence (PL), Raman spectroscopy (RS), and photo-absorption measurements. Raman scattering experiments show optical phonons of the GaAs (at ~280 cm-1 for the longitudinal and at ~267 cm-1 for the transverse modes) and GaN (at 465 cm-1) types as well as disorder activated acoustical phonons (at 80 and 190 cm-1). The frequency of the GaAs-type longitudinal optical phonon shows strong dependence on the GaN content. A strong diagonal component, forbidden in zinc blende structure, is observed for both types of optical phonons. The activation of these components by trigonal GaN3As microclusters was established by bond polarizability model analysis of the Raman selection rules. We also observe a confined GaAs optical mode (at 255 cm-1) indicating local ordering (anti-clustering) of As and N atoms in the alloy lattice.

Thursday AM, June 25, 1998

Session N. Epitaxial Growth: Alloys and Doping

Room: 005
Location: Olsson Hall

Session Chairs: Russ Dupuis, University of Texas; Mike Tischler, Mesa, AZ 85210

8:20 AM, N1

MOVPE Growth of GaNAs Using Arsine and Dimethylhydrazine: CARL ASPLUND[1]; Mattias Hammar[1]; Gunnar Landgren[1]; [1]Royal Institute of Technology (KTH), Department of Electronics, Laboratory of Semiconductor Materials, Electrum 229, S-164 40 Kista Sweden

GaInNAs has recently attracted much attention due to its potential role as a long-wavelength (⊕1.3 um) material, lattice-matched to GaAs substrates. In this study, GaNAs layers with excellent morphology have been grown on GaAs in a low-pressure MOVPE reactor using arsine and dimethylhydrazine (DMHy). The material quality was evaluated by HR-XRD, AFM, SIMS and PL measurements. The growth rate was found to decrease from 3.6 to 0.7 μm/h as the growth temperature was reduced from 630 to 500ϒC, while the N uptake rose dramatically. It was also found that the nitrogen concentration in the samples increased with the [DMHy]/([AsH_3]+[DMHy]) partial pressure ratio in the growth chamber, which varied between 0.89 and 0.97. At 500ϒC a nitrogen content as high as 5% was achieved. Preliminary results for GaInNAs will also be reported.

8:40 AM, N2

Epitaxial Growth of InGaAsN/GaAs Using Dimethylhydrazine : CAIXIA JIN[1]; Yueming Qiu[1]; S. Francoeur[1]; S. Nikishin[1]; Henryk Temkin[1]; [1]Texas Tech University, Dept. Electrical Engineering, MS 3102, Lubbock, TX 79409 USA

Alloys of InGaAsN and related heterostructures attract attention due to their wide range of possible optoelectronic applications. Plasma-assisted nitrogen sources are commonly used for growth of these materials. This results, however, in ion-induced damage and inferior optical properties of epitaxial layers. We demonstrate here high quality molecular beam epitaxy with dimethylhydrazine (DMHy) as an alternative nitrogen source. We describe systematic experiments on the growth of high quality GaAsN and InGaAsN/GaAs superlattices (SLs) by metalorganic molecular beam epitaxy (MOMBE) using solid As, triethylgallium (TEG), and DMHy. The epitaxial growth was carried out on (001)GaAs substrates at growth temperatures between 400 and 550 ϒC. Single phase GaAsN with nitrogen composition up to 3% and InGaAsN/GaAs SLs were evaluated by high resolution x-ray diffraction (HRXRD), secondary ion mass spectroscopy (SIMS), photoluminescence (PL), and transmission electron microscopy (TEM). Surprisingly, at low growth temperature the GaAsN growth rate and the nitrogen incorporation are strongly dependent on the DMHy flux. For instance, the growth rate at 450oC decreases from 0.8 μm/hr in GaAs to only 0.4 μm/hr for GaAsN with DMHy feed pressure of 7 torr. At higher temperatures, the growth rate is only weakly dependent on the DMHy flux, but the nitrogen incorporation is less efficient. We propose a model based on formation of an adduct of TEG and DMHy in the near surface transition layer to explain the growth kinetics of GaAsN. Layers of GaAsN grown with DMHy are single

phase, as determined from HRXRD measurements, and show much better room temperature PL efficiency than that obtained on layers grown with plasma nitrogen source at similar conditions. The use of DMHy as a nitrogen source also allows for the preparation of high quality InGaAsN/GaAs SLs. Very sharp and distinct satellite peaks, as well as Pendellösung fringes, are observed in HRXRD for InGaAsN/GaAs SLs, indicating good crystalline quality, lateral uniformity and vertical periodicity. Excellent agreement between dynamic simulations and experimental data suggests that the SLs interfaces are atomically sharp. The nitrogen incorporation in InGaAsN/GaAs SLs was further confirmed by SIMS measurements.

9:00 AM, N3+

Solid Source MBE Growth of InAsP/InP Quantum Wells: GEORGIANA DAGNALL[1]; Tong-Ho Kim[1]; Robert A. Metzger[1]; Stuart R. Stock[2]; April S. Brown[1]; [1]Georgia Institute of Technology, School of Electrical and Computer Engineering, Microelectronic Research Center, 791 Atlantic Dr., Atlanta, GA 30332-0269 USA; [2]Georgia Institute of Technology, School of Material Science and Engineering, Bunger Henry Building, 778 Atlantic Dr., Atlanta, GA 30332-0245 USA

The use of strained InAsP quantum well structures in lasers has resulted in record high temperature operation and low threshold current densities. Due to recent developments in solid phosphorous and arsenic sources, combined with the inherent safety advantages of solid sources as compared to gas sources, the solid source approach for the growth of phosphorous and arsenic containing compounds is becoming more widespread. To our knowledge, an extensive study of the effects of growth conditions (substrate temperature, arsenic species) on arsenic incorporation and material quality has not been previously published. Herein, we report on the structural and optical properties of strained $InAs_{0.4}P_{0.6}$/InP multi-quantum well (MQW) structures containing five 50Å wells. In particular, we focus on the effects of the growth conditions by solid source MBE (SSMBE), specifically substrate temperature (420-535°C) and As species, As_2 or As_4. The switching conditions of the Group V flux at the normal and inverted interfaces were different in order to minimize source roughening and flux transient effects. The composition and the thickness of the barriers and the wells were determined using Θ-2Θ x-ray diffraction analysis. The optical quality of the grown material was characterized with 300K and 77K photoluminescence measurements and 300K absorption measurements. High quality InAsP MQW's grown with As_2 or As_4 showed sharp excitonic structure in 300K absorption spectra. For both As_2 and As_4 77K PL FWHM measurements indicated a minimum in material quality at intermediate growth temperatures (approximately 470ϒC). Generally, growth with As_4 produced better structural and optical material than did growth with As_2. Sharp satellite peaks (up to 9 orders) were observed in the x-ray diffraction data for growths under all conditions; however growth with As_4 produced the sample with the best quantum well uniformity. In addition, the narrowest 77K PL FWHM of 26 meV was obtained for growth under an As_4 flux as compared to 31 meV for growth with an As_2 flux. Surprisingly, the arsenic composition in the wells was not significantly affected by the arsenic species. The incorporation of arsenic was approximately the same in the InAsP wells for either an As_2 flux or an As_4 flux (2-3% lower in the As_2 wells) but was enhanced 2-3 times in the InP barriers for structures grown using As_2 (unintentional As% in InP barrier = 2-3%) as compared to growth using As_4 (unintentional As% in InP barrier = 0.6%). As indicated by the 300K PL and absorption measurements, the optical quality of the As_4 samples improved as the substrate temperature increased, this improvement continuing until indium began to desorb from the growth surface at a temperature of 535°C. Unlike the structures grown with As_4, the 300K photoluminescence and structural quality of MQW's grown with As_2 showed little sensitivity to substrate temperature.

9:20 AM, N4

InGaAlAs Digital Alloys for Near-Infrared Broadband Light-Emitting Diodes: I. J. FRITZ[1]; M. Hafich[1]; J. F. Klem[1]; S. A. Casalnuovo[1]; [1]Sandia National Laboratories, P.O. BOx 5800, Albuquerque, NM 87185-0603 USA

For various applications in the near-infrared, we have been developing broadband LEDs using multiple quantum wells emitting at different wavelengths, These devices require incorporation of a variety of layers with different band gaps without strain-induced dislocations. We have developed a novel approach to this problem using short-period superlattices (digital alloys) combining ternary and quaternary InGaAlAs layers grown by MBE on InP substrates. A typical structure has three quantum wells emitting at ~1350, 1575 and 1800 nm. The well and barrier materials are short-period superlattices of $In_{0.66}Ga_{0.34}As$ and $In_{0.41}Ga_{0.21}Al_{0.38}As$ with appropriate thickness ratios. The wells are in compression, with strain balance provided by tension in the barriers and confinement layers. With careful choice of barriers widths, nearly balanced emission from the three wells has been achieved. * Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U. S. Department of Energy under Contract DE-AC04-94AL85000.

9:40 AM, N5

Characteristics of InP Based Quaternary Materials Grown by LP-MOVPE Using TBA And TBP In Nitrogen Ambient: DIETMAR KEIPER[1]; Ralf Westphalen[1]; GUNNAR LANDGREN[1]; [1]Royal Institute of Technology (KTH), Department of Electronics, Electrum 229, 164 40 Kista, Stockholm Sweden

Abstract submitted as a contribution under the topic "Epitaxial Techniques" In the standard MOVPE process toxic hydrides PH_3/AsH_3 as V-precursors and highly explosive H_2 as carrier gas are used. Therefore many alternative, less toxic group V-sources have been investigated and e.g. 1.3µm laser structures grown in H_2 ambient with the alternative group V-precursors Tertiary butyl arsine (TBA) and Tertiary butyl phosphine (TBP) show state of the art device performance. The usual growth parameters for TBA/TBP are 80mbar and 620°C. Since some years efficient N_2 purifiers are available and GaAs- respective InP-based materials are grown with N_2 carrier gas. The electrical and optical characteristics are evaluated and show improvements in material quality. Furthermore, the wafer uniformity is increased with N_2 as carrier gas. For the N_2 process it is recommended to halve the V/III ratio compared to the H_2 process. Furthermore, to achieve the same growth rate in N_2 like in H_2 a reduced total gas-flow is necessary and thus the total pressure has to be reduced to keep the gas-velocity constant. Concluding, utilization of both less toxic and liquid TBA/TBP as group V-precursors and inert N_2 as carrier-gas offers a potential for a dramatic improvement in the safety of MOVPE growth (inherent safe) in combination with increased uniformity and materials quality. We have investigated for the first time the MOVPE growth of InP-based materials grown with TBA/TBP in N_2. The MOVPE growth was performed on annealed InP:S wafers with (001)±0.3° orientation in an Aixtron 200/4 system. The surface quality of the typically 300nm thick layers was evaluated by Nomarski phase-contrast optical microscopy. The composition and superlattice period was measured by x-ray diffraction (HRD). The later one was determined within an accuracy of better than ±2%. The band-gap was determined by room-temperature PL-measurement. The carrier concentrations and mobilities of the intentionally undoped layers were evaluated by Hall measurement with van de Pauw geometry. Our investigations have shown that defect free (<25defects/cm^2) deposition of the alloy $In_{(1-x)}Ga_xAs_yP_{(1-y)}$/InP is possible by using the combination of TBA/TBP as V-precursor and N_2 as carrier gas. The electrical characteristics of the samples produced by the safe process are similar or even better than those of the standard process. The solid composition (xs,ys) dependence on the gas-phase composition (xg,yg) is evaluated for InGaAsP material grown on InP with TBA/TBP in N_2 ambient. Compared to the standard process is the function ys = ys(yg) for different InGaAsP alloys closer to a linear relation. Furthermore, the effect of the V/III ratio on this (xs,ys)-(xg,yg) dependence is investigated. Thus the approximate function yg=yg(xg,V/III) for (xs,ys)=constant (unequal to zero) is determined. Further growth details, like the composition shift of InGaAsP/InP and device structures on InP will be presented.

10:00 AM Break

10:20 AM, N6

The Problem of Beryllium Dopant In-Diffusion and the Use of Silicon as an Alternative P-Type Dopant in (110) GaAs Epitaxial Layers: ELIAS TOWE[1]; Jian Xu[1]; [1]University of Virginia, Laboratory for Optics and Quantum Electronics, Charlottesville, VA 22903-2442 USA

In solid-source molecular beam epitaxy, beryllium is the most commonly used p-type dopant. Beryllium, however, segregates and diffuses into regions where it may not be desirable in (001) GaAs-based heterostructures. The segregation and diffusion problems are especially serious in [110]-oriented heterostructures. We have grown several sets of p-i-n (In,Ga)As/GaAs multiple quantum well structures by molecular beam epitaxy on (110) GaAs substrates. One set of samples uses beryllium as the p-type dopant; the other set takes advantage of the amphotericity of silicon, under appropriate growth conditions, to achieve both p- and n-type doping on the (110) surface. Photoluminescence and absorption spectra—both at room and liquid nitrogen temperatures—show that the beryllium doped p-i-n structures are of inferior quality when compared to the all-silicon doped structures. TEM photo-micrographs clearly show the beryl-

lium in-diffusion and disordering of the multiple quantum well structures in the diodes that are doped with beryllium; hence the reason for their inferiority. We have fabricated some p-i-n optical modulator diodes using silicon as the dopant for both the p- and n-type layers on the (110) GaAs substrates. Our results show that the devices have excellent operating characteristics, including some that are unique to the (110) surfaces.

10:40 AM, N7

Increase of Carbon-Doping Efficiency in Lattice-Strain-Free InGaAsP Quaternary Alloy Grown By Gas-Source Molecular Beam Epitaxy Using CBr_4: KIYOSHI OUCHI[1]; Tomoyoshi Mishima[1]; Kazuhiro Mochizuki[1]; Tohru Oka[1]; Tohru Nakamura[1]; [1]Central Research Laboratories, Hitachi Ltd., Optoelectronics Research Dept., 1-280 Higashi-Koigakubo, Kokubunji, Tokyo 185-8601 Japan

We previously reported high-performance InGaP/GaAs and InP/InGaAs heterojunction bipolar transistors (HBTs) with record cut-off frequencies grown by gas-source MBE. The key technology in the HBTs is the growth of high quality base layers doped with extremely heavy carbon using CBr_4 source. Here we report the remarkable increase in carbon-doping efficiency in InGaAsP for the first time, which is expected to be applied as a new base layer. Use of carbon-doped InGaAsP (InGaAsP:C) quaternary alloy has been expected to improve the performance of HBTs because of the flexible design of the base layer. Lattice matched InGaAsP:C and compositional graded layer can be grown by adequate compositional control, where electron transport is accelerated by built-in electric field. However, the electric properties of InGaAsP:C will not be simple as the amphoteric behavior of carbon is generally enhanced with the increase in In composition in InGaAs:C. The influence of alloyed P has not been clarified yet. The $In_{0.1}Ga_{0.9}AsP$:C layers were grown on the semi-insulating GaAs substrate by gas-source MBE using CBr_4 as carbon source. The In composition was fixed to 0.1, and P composition was controlled from 0 to 0.08 by changing the ratio of AsH_3 and PH_3 flow rate. CBr_4 was supplied without a carrier gas by using a closed-loop pressure control system. InGaAsP:C layers showed a high carrier concentration of $2.6x10^{20}$ cm^{-3}, which was roughly three times higher than those of as-grown similar materials by MOCVD. The carbon-doping efficiency of InGaAsP:C was higher for 30% than those of GaAs:C grown at the same growth conditions. Such enhanced doping efficiency has never been reported. The doping efficiency was independent of P composition up to 8%, which enabled lattice-matched growth of InGaAsP:C on GaAs substrate. This will lead to the fabrication of reliable HBTs. The extremely heavily carbon-doped InGaAsP is thus a very promising material for an ultra-high-speed HBT with the structure of a compositional graded InGaAsP:C base layer.

11:00 AM, N8

Efficient Doping and Bright Room Temperature Photoluminescence from Solid-Source MBE $Al_{0.3}Ga_{0.7}$ Using Carbon Tetrabromide: Miro Micovic[1]; Dimitri Lubyshev[1]; Weizhong Cai[1]; Navid Gratteau[1]; D. L. MILLER[1]; Ken Bacher[2]; [1]Penn State University, 121 Electrical Engineering East Bldg., University Park, PA 16802 USA; [2]QED, Inc., 119 Technology Drive, Bethlehem, PA 18015 USA

Although carbon tetrabromide is a common precursor for C doping of GaAs and InGaAs grown by molecular beam epitaxy (MBE), its use in doping AlGaAs has not been extensively covered in literature. We have studied the hole density, carrier mobility, and surface morphology of CBr_4-doped $Al_{0.3}Ga_{0.7}As$ layers grown by solid source MBE for substrate temperatures ranging from 560 ℃ to 700℃. We have found that the doping efficiency and mobility are independent of substrate temperature over this wide range, and that carbon acceptors are incorporated into $Al_{0.3}Ga_{0.7}As$ and GaAs with identical efficiency. The resulting material exhibits very bright room temperature photoluminescence with a peak wavelength of 670 nm. The luminescence can be see even under excitation with a household flashlight. A series of samples with 1 micron thick $Al_{0.3}Ga_{0.7}As$ layers intentionally C-doped using CBr_4 to $p = 1.4 \times 10^{19}$ cm^{-3} was grown in parallel with a series of undoped control samples. Substrate temperature was varied in 20℃ steps between 560℃ and 700℃ for both series. Aluminum composition x of the undoped reference samples deviated less than ± 0.3% from the intended value of x=0.3 for samples grown at substrate temperatures below 630 ℃, as determined by double crystal x-ray diffraction. At 680 ℃ and 700 ℃ Ga re-evaporation caused a measurable increase in Al mole fraction. All of the doped and undoped $Al_{0.3}Ga_{0.7}As$ samples had a hazy surface morphology when grown in the temperature range between 600℃ and 640℃. Despite the hazy surface at intermediate temperatures and the loss of several percent of Ga at 700 ℃, Hall effect measurements showed that the CBr_4 doping efficiency and carrier mobility were independent of the substrate temperature to within ±10% for the As/Ga fluxes used. Carbon doping resulted in a constant difference of about 20 arcsec between the $Al_{0.3}Ga_{0.7}As$ (004) Bragg reflections from the undoped and doped layers, referenced to the GaAs substrate. This is agrees well with the lattice contraction observed in our C-doped GaAs layers at the same carbon concentration. In summary, we have demonstrated that CBr_4 is a well behaved p-type doping precursor for $Al_{0.3}Ga_{0.7}As$ in solid source MBE over a wide range of substrate temperatures, producing layers of excellent electrical and optical properties.

11:20 AM, N9

Oxygen-Doped AlGaAs Grown by MOVPE For GaAs Field Effect Transistors: NOBORU FUKUHARA[1]; Yuichi Sasajima[1]; Masahiko Hata[1]; Takayoshi Maeda[1]; [1]Sumitomo Chemical Co., Ltd., Tsukuba Research Laboratory, 6 Kitahara, Tsukuba, Ibaraki 300-3294 Japan

A high resistive oxygen-doped AlGaAs(AlGaAs:O) has been successfully grown by MOVPE, and the characteristics of field effect transistors (FETs) fabricated on the oxygen-doped AlGaAs buffer were studied with emphasis on the material properties. Properties of a buffer layers which are inserted between FET's active layer and semi-insulating GaAs substrate greatly affect characteristics of FETs, thus controlling or designing a buffer becomes an important issue for making epitaxial wafers for FETs. Epitaxial layers in this work were grown by low pressure MOVPE. AlGaAs:O layer were grown at in range 650 to 725 ℃ using normal-hexylether as an oxygen source. Oxygen concentration up to $10^{19}cm^{-3}$ were obtained without surface degradation within a wide range of Al composition (0.2 to 0.7). Oxygen-related levels in high resistive AlGaAs:O were investigated by applying isothermal capacitance transient spectroscopy (ICTS) method to MIS(Al/AlGaAs:O/n-GaAs) diode. A characteristic broad signal was observed in the ICTS spectra and found to have a good correlation with oxygen concentration and photoluminescence intensity. Recess gated MESFETs were fabricated on the epitaxial wafers, being consist of n-GaAs active layer/ undoped AlGaAs buffer layer(0.3- 0.5γm)/AlGaAs:O buffer layer(0.5γm)/ S.I.substrate. Undoped AlGaAs buffer was inserted to improve the quality of MESFETs by preventing the channel layer from contacting with AlGaAs:O. The leakage currents through the i-AlGaAs/AlGaAs:O buffer layer were measured using AuGe/Ni/Au and AuZn/Au electrodes directly formed on the buffer layer after stripping active layer and it was found that both of electron and hole leakage currents decreased with increase in oxygen doping. As a result, good pinch-off characteristics was observed even at elevated temperature up to 200℃. Beside the good DC-IV characteristics, a sidegating effects were significantly reduced, when oxygen doping concentration in the AlGaAs:O reached high as about $10^{19}cm^{-3}$ in atomic concentration; sidegate threshold voltages larger than -40V were obtained with the sidegate distance of 10 m from FET's electrodes, while those voltage without AlGaAs:O buffer were about -6V. It suggests that the electronic potential of the buffer layer is effectively stabilized by introducing a number of recombination centers, just like as in low-temperature-grown GaAs by MBE. Other electrical characteristics of the FETs will be reported in detail.

11:40 AM, N10

Effects of the In/Ga Ratio on the Chemical Beam Epitaxial Growth of Si-Doped GaInP: R. ARES[1]; D. A. Clark[1]; W. T. Moore*[1]; R. W. Streater[1]; [1]NORTEL Advanced Technology Laboratory, Dept: 5C14, Mail Stop #29, P.O. Box 3511 Station C , Ottawa, Ontario K1Y 4H7 Canada

GaInP has generated a lot of interest in recent years in the field of high speed telecommunications for its key role in the manufacturing of devices such as heterojunction bipolar transistors (HBT) and high electron mobility transistors (HEMT). In such structures the alloy is usually intended to be lattice matched to GaAs. Due to normal variations in the growth parameters during production, the lattice mismatch can be expected to vary slightly from sample to sample. In this work we report on the effects of changes in the lattice matching condition up to +/- 2% on the electrical and optical characteristics of the layers. Hall effect measurements across 4 inch diameter wafers showed that the amount of active Si decreased by as much as 25% for Ga rich conditions but remained unchanged for In rich layers. Secondary ion mass spectrometry (SIMS) data confirm that the difference resides in a lower activation of the impurities and not in a lower Si incorporation in the layer. The activation efficiency was measured to be around 70% for lattice matched and In rich condition and monotonically dropped to 50% for the 2% Ga rich sample. Photoluminescence (PL) measurements taken over the entire surface of the wafers showed that the slightly In rich

alloy displayed a much increased sensitivity to temperature variations during growth. The full wafer PL uniformity was significantly worsened by a drift towards In rich conditions. Resistivity maps confirmed the observation, with the resistivity remaining stable at around 1% standard deviation for lattice matched and Ga rich layers and increasing to 70% standard deviation for a 2% In rich layer. Since the PL uniformity of In rich layers is so sensitive to the wafer temperature distribution during deposition, we have used the effect to investigate a variety of wafer holder and clip designs. In this way we were able to identify the major flat (MF) area as the main source of the temperature variations. Using a new clip design, we have been able to eliminate the effect of the MF on the layer uniformity. Full wafer PL maps will be shown to illustrate these results. *Present address: JDS Fitel, Ottawa, Ontario, Canada.

Thursday AM, June 25, 1998

Session O. Optical Characterization of Quantum Structures

Room: E316
Location: Thornton Hall

Session Chairs: Ben Shanabrook, Naval Research Lab, Washington, DC USA; Dieter Bimberg, Inst. fuer Festkoerperphysik, Tu Berlin 10623, Germany

8:20 AM, O1+

Characteristics and Physical Processes in InAs/GaAs Self-Organised Quantum Dot Lasers: LEE HARRIS[1]; David Mowbray[1]; Maurice Skolnick[1]; Mark Hopkinson[2]; Geoff Hill[2]; [1]University of Sheffield, Department of Physics, Hicks Building, Hounsfield Road, Sheffield, South Yorkshire S3 7RH England; [2]University of Sheffield, Electronic and Electrical Engineering, Mapin Street, Sheffield, South Yorkshire S1 3JD England

Characteristics and physical processes in self-organized InAs/GaAs quantum dot lasers are described. The discrete, atomic-like density of electronic states of a quantum dot system is expected to have a number of potential advantages for injection lasers. In particular, low threshold current densities (J_{TH}), high temperature stability of J_{TH} and high differential gains have been predicted. Until very recently studies of quantum dot based lasers were not possible due to the lack of systems exhibiting the necessary high optical quality. However, advances in epitaxial growth technology, in particular self-organized techniques, now allow the fabrication of dense arrays of quantum dots having a high optical quality. In addition, the small size of the dots and the resultant large energy level separations (~70meV >>kT\@300K) provides the possibility for devices operating at room temperature. We will present the results of a study of the device characteristics and physical processes occurring in InAs/GaAs self-organized quantum dot based lasers. At 80K a very low J_{TH} of 20Acm^{-2} has been obtained. For long cavities (~2mm), which lase via the dot ground state transition, J_{TH} is almost temperature insensitive up to 200K. However, for shorter cavities, which lase at higher energies corresponding to excited dot states, Jth increases rapidly above 100K as carriers are thermally evaporated from the excited dot states. The Hakki-Paoli technique has been used to determine the gain spectra as a function of injection current. Large period modulations of the gain are observed which results in spectrally separated groups of lasing modes above threshold. This behaviour is discussed in terms of the discrete nature of the dots. An analysis of the gain spectra allows the material and differential gain of the dots to be deduced. Because of their discrete nature carriers captured by different dots may be unable to interact directly and it has been predicted that a quantum dot system may lack a global Fermi level. This is in strong contrast to conventional lasers where a well defined Fermi level is pinned at threshold, resulting in a saturation of the spontaneous emission and other loss processes. The absence of a global Fermi level is used to explain the lasing spectra of our devices where the number of lasing modes increases above threshold. However studies of the spontaneous emission show an unexpected saturation close to threshold. Models for this latter behaviour will be discussed. Given the above characteristics, the suitability of quantum dot lasers for practical applications will be discussed.

8:40 AM, O2+

Controlled Spontaneous Lifetimes from InGaAlAs Quantum Dots Confined in Microcavities: L. A. GRAHAM[1]; D. L. Huffaker[1]; Q. Deng[1]; D. G. Deppe[1]; [1]University of Texas at Austin, Department of Electrical and Computer Engineering, Microelectronics Research Center, Austin, TX 78712-1084 USA

Controlled spontaneous emission lifetimes are observed in a planar semiconductor/dielectric microcavity with quantum dot emitters. Previously, large modifications of the angular direction of spontaneous light have been reported in these microcavities,1,2 but the predicted corresponding lifetime changes were relatively weak. In addition, previous experiments using quantum well emitters were complicated by the need to temperature tune the quantum well spectral peak with respect to the cavity resonance, thereby complicating the interpretation of the measurements. Using quantum (QD) dot emitters in the microcavity allows us to overcome these difficulties. Compared to quantum wells which have a high rate of dephasing from the intraband scattering of carriers, QDs can emit sharp spectral lines with the frequency of emission set by the dot shape and size. Inhomogeneous spectral broadening caused by fluctuation in dot size then provides a means for studying the lifetime changes due to emitter placement and cavity design. The epitaxial part of the microcavity was grown on an undoped GaAs substrate using molecular beam epitaxy. It consists of 15.5 pairs of GaAs/AlAs distributed Bragg reflectors (DBRs), a 0.13 micron GaAs cavity spacer, and QDs made from 6 monolayers of In0.5Ga0.35Al0.15As. The QDs are then covered by another 100 angstroms of GaAs and another single GaAs/AlAs pair. 3 pairs of MgF/ZnSe were later e-beam deposited for the top DBRs. Using this QD microcavity structure, we have been able to observe the dependence of spontaneous emission lifetime on wavelength around the spectral peak of the QD microcavity photoluminescence (PL). With the resonant wavelength of the QD microcavity at ~9514 Å, the spontaneous lifetime is 3.3 ns at 9575 Å and 2.5 ns at 9475 Å. We attribute the inhibited spontaneous emission on the longer wavelength side of the resonance to the cutoff of cavity modes in this direction. Conversely, we attribute the enhanced spontaneous emission on the short wavelength side to the presence of additional transverse modes. In addition, by measuring the lifetime at many points along the PL spectral peak, we are able to show that this change in spontaneous emission lifetime is consistent with the expected modification of the spontaneous emission lifetimes for this type of microcavity structure. Since the total emission rate and therefore the lifetime in a semiconductor/dielectric microcavity such as this is given by a summation of the emission rates into all solid angles including dominant lateral waveguide emission, this lifetime change is only around 30%. References[1] D.L. Huffaker, Z. Huang, C. Lei, D.G. Deppe, C.J. Pinzone, J.G. Neff and R.D. Dupuis, Appl. Phys. Lett. 60, 3203 (1992). [2] Y. Yamamoto, S. Machida, K. Igeta, and G. Bjork, in Coherence, Amplification, and Quantum Effects in Semiconductor Lasers, edited by Y. Yamamoto (Wiley, New York, 1991).

9:00 AM, O3+

Shot-Noise-Limited Adaptive Holographic Homodyne Ultrasound Detection: INDRAJIT LAHIRI[1]; Laura J. Pyrak-Nolte[1]; Micheal R. Melloch[2]; David D. Nolte[1]; R. A. Kruger[3]; G. D. Bacher[4]; M. B. Klein[4]; [1]Purdue University, Department of Physics, 1396 Physics Building, West Lafayette, IN 47907-1396 USA; [2]Purdue University, School of Electrical & Computer Engineering, 1285 EE Building, West Lafayette, IN 47907-1285 USA; [3]Indiana University Medical Center, Department of Radiology, Indiana University, Indianapolis, IN 46202 USA; [4]Lasson Technologies, 1331 Avenida de Cortez, Pacific Palisades, CA 90272 USA

We present a self-adapting holographic homodyne detector whose sensitivity approaches the quantum noise limit. The physical process is uniquely different than standard square-law homodyne detectors. Photorefractive multiple quantum wells act as adaptive beamsplitters to coherently detect phase modulated laser beams by performing real-time adaptive holography that can precisely measure surface ultrasound vibrations. They have the unique ability to achieve maximum linear homodyne by tailoring the excitonic spectral phase of quantum-confined excitons. Laser-based ultrasound is a promising nondestructive evaluation technique for remote sensing, manufacturing diagnostics and in-service inspection for many industrial applications. Non-adaptive homodyne and heterodyne reference beam interferometers could not operate effectively with speckle and time-delay interferometers require path length stabilization to a fraction of an optical wavelength. In this work we use photorefractive

quantum well thin films which combine the advantages of large excitonic electroabsorption with large carrier mobilities to produce high-sensitivity holographic devices that operate at extremely low light intensities, operating close to the quantum noise limit in the presence of speckle and do not require path length stabilization. The devices were grown by molecular beam epitaxy on semi-insulating GaAs substrates at 600 °C. The active electro-optic layers consisted of a 100 period multiple quantum well layer of 70 Å GaAs wells and 60 Å 30% AlGaAs barriers. The superlattice was proton implanted, epoxied to glass and the substrate removed to perform optical transmission experiments. Titanium-Gold contacts were evaporated to apply electric fields in the plane of the quantum wells. Degenerate two-wave mixing was performed using a CW Ti:Sapphire laser to investigate the detection sensitivity. Coherent laser beams cross inside the sample producing interference fringes. The generated electron-hole pairs screen the applied electric field by trapping at defects. The trapped space charge produces a modulation of the internal electric field which produces a spatially varying absorption coefficient and refractive index. The spatially modulated optical properties act as diffraction gratings. Homodyne detection in photorefractive quantum wells depends on the phase relationship between the diffracted reference beam and the transmitted signal beam. A key figure of merit in evaluating the performance of an ultrasonic receiver is the noise equivalent surface displacement (NESD) which is the minimum surface displacement detectable for a signal-to-noise ratio equal to unity for a 1 Hz detection bandwidth and 1 W power incident on the detector. We achieve a NESD of 9.4 x 10^{-7} Å(W/Hz)$^{1/2}$, within a factor of 3 of the shot noise limit. In conclusion we have demonstrated the operation of a novel laser-based ultrasound receiver based on two-wave mixing in photorefractive multiple quantum wells, operating close to the quantum noise limit. We have also demonstrated the ability to tune to quadrature by using the excitonic spectral phase. The tunability and sensitivity of these devices make them the best candidates for applications in industrial markets.

9:20 AM, O4+

Local Field Effects in Semiconductor Nanocrystals: MOHAMED DIB[1]; Maria Chamarro[1]; Philippe Lavallard[1]; Olga Lublinskaya[2]; Alexei I. Ekimov[2]; [1]Groupe de Physique des Solides, CNRS-Universités Paris 6 & 7, Tour 23, 2 place Jussieu, 75251 Paris Cedex 5, France; [2]A.F.Ioffe Physico-Technical Institute, Russian Academy of Sciences, 194021 St Petersburg, Russia

Differences between the optical properties of bulk semiconductor and nanocrystal (NC) are mainly determined by two physical phenomena: the electron-hole confinement effect and the local field effect. Firstly, the electron-hole pair generated in a small NC by optical absorption is spatially confined in a three-dimensional potential quantum well. As a consequence, the excited states are discrete and occur at a higher energy than in bulk material. This effect has been previously extensively studied. However, the effects related to the inhomogeneity of the medium have been generally neglected in semiconductor NCs. Indeed, the electric field inside a spherical NC with a dielectric constant ε_{NC}, embedded in a host characterized by ε_h, is resonantly enhanced when ε_{NC}=-$2\varepsilon_h$. This resonance depends on the dielectric function of the NC and consequently on the NC size and crystalline structure. In this paper we calculate the local-field effects on optical transitions as a function of size for cubic and wurtzite NCs and compare the calculation to experimental data obtained for wurtzite CdSe and cubic CdS NCs embedded in a glass and a silica gel matrix, respectively. Size-selective spectroscopic techniques have been used in order to avoid the inhomogeneous broadening due to the size dispersion. We show that taking into account the dielectric effects of the medium introduces an additional blue-shift of the absorption lines proportional to the oscillator strength of the transition and inversely proportional to the volume of the NC, which is in good agreement with the experimental results.

9:40 AM, O5

Strain Induced Exciton Alignment in Self-Assembled Quantum Dots: ARTHUR W.E. MINNAERT[1]; Andrei Yu. Silov[1]; Willem Van der Vleuten[1]; Jos E.M. Haverkort[1]; Joachim H. Wolter[1]; [1]Eindhoven University of Technology, Department of Physics, Den Dolech 2, P.O. Box 513, Eindhoven, Brabant 5600 MB The Netherlands

Strong phonon replicas, which are in contradiction with the predicted phonon bottleneck, have been observed under selective excitation of Self-Assembled quantum Dots (SAD's) both by us and by Heitz et al.[1] and Farfad et al.[2]In addition to these experiments, we observe a cutoff of the inhomogeneously broadened PL-band when exciting at an energy of one GaAs-LO phonon energy above the ground state of the smallest dots. Since this feature is observed between one and two times the GaAs-LO phonon energy below the excitation energy, this cutoff is a clear manifestation of a cascaded phonon emission. In view of the phonon bottleneck, the question arises why we observe such a strong cascaded phonon process. We interpret this cutoff and the strong phonon replicas as being due to a strong Fröhlich or polar interaction between a strain induced polarized exciton in the SAD and LO-phonons. Cleaved-side photoluminescence experiments support this interpretation, since we observe a very strong p-type polarization of the photoluminescence, which is perpendicular to the polarization of a heavy-hole ground state in a quantum well. This p-type polarization is explained by an electron and hole wavefunction polarization due to the strain field. The resulting aligned excitons couple with LO-phonons by subsequent polarization and depolarization of the lattice, which is called the Fröhlich interaction. [1] R. Heitz et al., Appl. Phys. Lett. 68 (3), 361, (1996)[2] S. Farfad et al., Phys. Rev. B52 (8), 5752, (1995)

10:00 AM Break

10:20 AM, O6

Size Dependence of the Red-Shifted Luminescence in Semiconductor Nanocrystals: MARIA CHAMARRO[1]; Mohamed Dib[1]; Thierry Gacoin[2]; Guy Allan[3]; Christophe Delerue[3]; Michel Lannoo[3]; [1]Groupe de Physique des Solides, CNRS-Universités Paris 6 & 7, Tour 23, 2 place Jussieu, 75251 Paris Cedex 5 France; [2]Laboratoire de Physique de la Matière Condensée, Ecole Polytechnique, Route de Saclay, 91128 Palaiseau Cedex France; [3]Institut d'Electronique et de Microélectronique du Nord, ISEN, 41 Bd Vauban, 59046 Lille Cedex France

Absorption and luminescence spectra of Semiconductor Nanocrystals (SNCs) show inhomogeneously broadened bands even at low temperatures. Size-dispersion in studied samples is the main origin of the inhomogeneous width. By using size-selective spectroscopic techniques such as resonant photoluminescence (RPL) and photoluminescence excitation (PLE), it is possible to reduce the inhomogeneous contributions to the optical transitions. Both techniques are based on the use of a narrow energy window, either in excitation or in detection of the photoluminescence, which automatically selects SNCs with levels in the corresponding energy range. Recently, the use of these techniques has revealed the existence of a red-shift of the RPL in several SNCs: Si[1], CdSe[2], CdS[3], InP[4], InAs[5]. Red shift increases as size decreases and is accompanied by long lifetimes of emission. RPL has been attributed to an intrinsic origin: the emission of a spin-forbidden exciton state. That seems a universal behaviour, however size dependence of red-shift is a function of the material . We perform a tight-binding calculation with restricted configuration interaction in a typical case: very small cubic SNCs for which the electron-hole interaction is of the same order of magnitude as the spin-orbit interaction. We compare the theoretical calculation to the experimental results obtained for CdS nanocrystals embedded in a silica gel matrix. The good agreement between the theoretical and the experimental results allows us to attribute the red-shift of the resonant photoluminescence to the splitting between an optically-allowed exciton state and a spin-forbidden exciton state. We show that it is a function of the electron-hole exchange energy and the spin-orbit splitting and finally we generalize our conclusion to other cubic SNCs. (1) P.D.J. Calcott et al. J.Phys.Cond.Matter 5,L91 (1993). (2) M. Nirmal et al. Phys.Rev.Lett. 75,3728 (1995), M. Chamarro et al. Phys.Rev.B 53,1336 (1996)(3) M. Chamarro et al. Phys.Rev.B (in press)(4) O.I. Micic et al. J.Phys.Chem.B 101,4904 (1997)(5) U. Banin et al. Superlattices and Microstructures 22,559 (1997)

10:40 AM, O7

Resonant,Time and Spatial Resolved Photoluminescence from a Single Quantum Dot And Quantum Wire: VALIA VOLIOTIS[1]; Joel Bellessa[1]; Roger Grousson[1]; Xue Lun Wang[2]; M. Ogura[2]; H. Matsuhata[2]; [1]CNRS, Groupe de Physique des Solides, Tour 23, 2 Place Jussieu, Paris 75005 France; [2]Electrotechnical Laboratory, Process Fundamentals Section, 1-1-4 Umezono, Tsukuba, Ibaraki 305 Japan

Recent micro-photoluminescence (micro-PL) and micro-photoluminescence excitation (micro-PLE) spectroscopy [1-2] have revealed that one quatum wire (QWR) is segmented into extended sections of hundred of nanometers with slightly different confining potentials. Inside these sections, quantum boxes (QB) with a weak confining potential (10 meV in the case of our structure) and width comparable to the exciton Bohr radius, localize the carriers at low temperature. By means of resonant time resolved micro-PL we propose to investigate on radiative lifetimes and relaxation mechanisms in quantum wires and dots. The studied wires are V-shaped GaAs/AlGaAs QWRs grown by flow rate modula-

tion epitaxy, a modified MOVPE technique. Samples have been chemically etched and the (001) flat region and part of the (111)A sidewall AlGaAs have been removed in order to enhance the QWR PL signal. The main micro-PL line is splitted into sharp peaks of width less than 0.5 meV separated by a few meV. The micro-PLE spectra reveal also a fine structure which has been attributed either to excited states of the emiting box or to QWR states [1]. The presence of sharp peaks in the PLE spectra allow the resonant excitation of levels in a given QB and the observation of the time evolution of the fundamental transition. The observed radiative lifetimes of localized excitons are long, ranging from 300 to 500ps depending on the QB size in the free direction of the wire. This is in agreement with theoretical calculations of QB radiative lifetimes with a coherence volume equal to the total volume of the QB. In some experiments where the micro-PL of one QWR section is observed, the related radiative lifetime is shorter (150 ps) and agrees well with calculations [3]. The measured rise times are fast, ranging from a few ps (time resolution of our exprimental setup) to 100 ps. The dispersion in rise times gives us informations about the relaxation mechanisms between the QB levels. No phonon bottleneck is observed, but there is a clear dependence of relaxation times with the energy separation between levels. This was predicted theoretically in [4], where a quenching of the LA phonon emission rate was found. Auger relaxation mechanisms should not play any important role since our experiments are performed at low power densities when only one (or less) electron-hole pair is created in the dot. [1] J. Bellessa et al, Appl.Phys. Lett 71, 2481 (1997); Phys. Stat. Sol.,164, 273 (1997)[2] F. Vouilloz et al, Phys. Stat. Sol.,164, 259 (1997)[3] D. S. Citrin, Phys. Rev. Lett. 69, 3393, (1992)[4] U. Bockelmann et al, Phys. Rev. B 42, 8947 (1990)

11:00 AM, O8

Radiative Lifetimes of Localized Exciton in Single and Coupled Quantum Wires: KAZUHIRO KOMORI[1]; Xue Lun Wang[2]; Ryouichi Akimoto[2]; Fumio Sasaki[2]; Mutsuo Ogura[2]; [1]Electrotechnical Laboratory & JST , Optoelectronics Division, 1-1-4 Umezono, Tsukuba City, IBARAKI 305-8568 Japan; [2]Electrotechnical Laboratory, 1-1-4, Umezono, Tsukuba City, IBARAKI 305-8586 JAPAN

The temperature dependence of radiative exciton lifetimes of very small single and coupled GaAs/AlGaAs quantum wires with thickness of 5nm, and effective width of 20nm are investigated in order to clarify the localized exciton characteristics. The samples were fabricated by flow rate modulation epitaxy (FME) on a V-grooved substrate[1], and are consisted of single period crescent shaped GaAs/AlGaAs for single quantum wire, and two crescent shaped GaAs separated by a narrow AlGaAs barrier with different thicknesses of 1.5nm, 2nm and 3nm for coupled quantum wires[2]. These samples exhibit good photoluminescence (PL) characteristics with overall linewidth of 8meV which could be separated to several narrow lines of 0.5-0.2meV width by micro-PL measurements[3]. The radiative lifetimes are measured at various temperatures using mode-locked Ti:Sapphier laser with pulse width of 200fs. The excitation wavelength was tuned to 705nm between the exction wavelength of quantum wire (760nm at 10K) and quantum film on the (111) side walls (670nm at 10K) for quasi-resonant condition.'\@As to the temperature dependence of the radiative lifetimes of single and coupled quantum wires, the radiative component dominates below 150K while non-radiative one dominates above 150K. T he non-radiative component in these quantum wires is small and is comparable to that of quantum films showing high quality samples. Below 50K, the radiative lifetimes of single quantum wires show quasi quantum-dot characteristics, namely the characteristics of localized excitons, where the radiative lifetime of about 400ps is almost insensitive to the temperature. This is expected from the narrow PL lines in the micro-PL characteristics[3]. Also, the time-resolved photoluminescence exhibits red shift of 2meV for delays after their excitation. Above 50K, the thermalization of the localized exciton occurs and temperature dependence lies between linear and square root variations[4]. Weak localization characteristics are observed in the coupled quantum wires. The radiative lifetimes of the coupled quantum wires show small temperature dependence only under temperatures below 20K. The red shift in the time resolved photoluminescence is smaller than that of single quantum wires and varies from 1meV to 1.5meV with barrier thickness dependence. This can be explained by the different confinement and large effective radius of the exction in the coupled structure. Above this temperature, radiative lifetimes increase with temperature and exhibit dependence between linear and square root variations. The slope of radiative lifetimes versus temperature is decreased as the barrier thickness is decreased, (i.e., coupling strength is increased). This can be explained in terms of the oscillator strength caused by the asymmetrical coupling of each electron and hole. This is also explained by the distribution of wavefunction analyzed by finite element methods (FEM) and small absorption of ground level in PLE spectra. References[1] X. L. Wang, M. Ogura , Appl. Phys. Lett., 66 , 1506 (1995)[2] K. Komori, et.al, Appl. Phys. Lett., 68, 3787 (1996)[3] J. Bellessa, et. al., Appl. Phys. Lett., 71, 2481 (1997)[4] H.Akiyama, et.al., Phys. Rev. Lett. 72, 924. (1994)

11:20 AM, O9

Spin Relaxation Dynamics in GaAs Quantum Wires Analyzed by Transient Photoluminescence: TETSUYA NISHIMURA[1]; Xue-Lun Wang[2]; Mutsuo Ogura[2]; Atsushi Tackeuchi[3]; Osamu Wada[1]; [1]The Femtosecond Technology Research Association, FESTA Laboratories, 5-5 Tokodai, Tsukuba, Ibaraki 300-2635 Japan; [2]Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba, Ibaraki 305-8568 Japan; [3]Waseda University, Department of Applied Physics, 3-4-1 Ohkubo, Shinjuku-ku, Tokyo 169-8555 Japan

We report the first observation of shortening of electron spin relaxation time in GaAs/AlGaAs quantum wires due to strong confinement of electrons in quantum wires. The quantum wire samples with 8.5 nm GaAs thickness were fabricated on V-grooved GaAs substrates using flow rate modulation MOCVD and chemical etching technique. Quantum well samples with the same thickness were grown for comparison. Carrier recombination lifetime and electron spin relaxation time were analyzed from photoluminescence (PL) transients in a temperature range from 4 K to 250 K. The wavelength of mode-locked Ti:sapphire laser was tuned in a range of 755 to 780 nm so that only the quantum wires were excited. The PL transients were detected by a streak camera with 2 ps time resolution. A comparison of the temperature dependence of the recombination lifetime was made between quantum wells and quantum wires. It was found in a temperature range from 4 K to 30 K that the radiative recombination lifetime is proportional to the temperature T in quantum wells, and proportional to $T^{1/2}$ in quantum wires. Weaker temperature dependence in quantum wires was explained by the enhanced density of states as well as less effective thermalization against the temperature increase due to the one dimensional (1D) nature of quantum confinement. This result indicates that 1D electron confinement is achieved in these quantum wires. The spin polarization decay in GaAs/AlGaAs quantum wires was determined by analyzing the circularly polarized PL transients. Spin non-equilibrium condition was optically initiated by exciting the sample with a circularly polarized laser pulse, and the spin relaxation time was deduced from the polarization decay time. The spin relaxation time in quantum wires was 120 ps at 180 K being 3.5 times smaller than in quantum wells, and was also found to exhibit a stronger negative temperature dependence down to 50 K in comparison with quantum wells. Our previous analysis on quantum wells showed that the D'yakonov-Perel' mechanism based on the spin-orbit interaction is dominant in this temperature region (A. Tackeuchi, et al., Appl. Phys. Lett. 68 (1996) 797). On the basis of this mechanism, shorter spin relaxation time as have been observed in our quantum wires is attributed to stronger quantum confinement which leads to an increase of the spin splitting factor, resulting in an enhancement of the effective magnetic field to relax spin polarization. The present study has shown for the first time that the electron spin relaxation time is shortened in GaAs quantum wire due to the 1D electron quantum confinement. This result can also be applied for improving the speed of spin polarization all-optical switches.

11:40 AM, O10

Optical Absorption in Tensile-Strained GaAs/InAlAs Quantum Wells: QINGRU MENG[1]; Theda Daniels-Race[1]; Zhijiong Luo[2]; Laurie E. McNeil[2]; [1]Duke University, Department of Electrical Engineering, PO Box 90291, Durham, NC 27708-0291 USA; [2]University of North Carolina at Chapel Hill, Department of Physics and Astronomy , Phillips Hall, CB #3255, Chapel Hill, NC 27599-3255 USA

In recent years, optical properties of quantum wells have been studied extensively on lattice-matched III-V material systems, particularly in the GaAs-AlGaAs and InGaAs systems. However, examination of electro-optic phenomena related to strained InAlAs films has, in comparison, received considerably less attention. In addition, for next generation opto-electronics, the realization of polarization insensitivity remains a significant challenge. Difficulties imposed by the randomization of initially polarized signal-carrying light motivate examination of materials and bandgap engineered structures to manipulate the polarization independent response. Our work and that by other groups has shown that tensile strained material systems are promising alternatives in the development of polarization independent behavior, and hence device structures, for future

optical communication systems. In this work, tensile strained GaAs/InAlAs coupled quantum wells with various doping profiles are investigated for observation of polarization independent behavior under bias. In these structures, biaxial strain ranging from 0.5% to 0.7% is applied lifting the heavy hole/light hole degeneracy at the center of valence band, thus raising the light hole level above that of the heavy hole. Asymmetric double quantum well (ADQW) widths are chosen such that the heavy hole level is nearest the top of the valence band in the thinner well, while the light hole level in the wider well is uppermost. This design allows transmission of both TE and TM modes of light when proper electric field is applied, thus achieving polarization independence. The samples were prepared by solid-source molecular beam epitaxy using a Riber 32 R&D MBE machine equipped with in-situ pryometer temperature monitoring and RHEED. Polarization sensitivity and electric field effects upon optical interband transitions are characterized via low temperature photoluminescence and photocurrent measurements. Theoretical analysis is conducted using the multilayer transfer matrix method(TMM) including excitonic and electric field effects. The states of direct and crossed excitons and their contributions to absorption are considered and compared. In an ADQW structure with well-barrier-well geometries of 100/30/40 Λ, the binding energy for direct 1e-1hh excitons is -8.2 meV. In turn, the crossed 1e-1hh excitons have a binding energy of only approximately -4 meV, which is comparable to the value in bulk material and the thermal broadening produced by optical phonon scattering. Therefore, the crossed excitons are relatively easy to dissociate. Moreover, due to the limited overlap of electron-hole wave functions, the oscillator strength, and thus the optical transition strength by crossed e-h pairs, is much weaker than that of direct excitons. According to calculation, the strength ratio of crossed excitons to direct excitons is about 1 to 500, corresponding to the ground interband transition in the ADQW structure mentioned above. Calculated transition energies under variable bias conditions are compared with measured results. Proof of principle demonstration of phenomena applicable to voltage-tunable polarization insensitive photodetection and modulation is presented.

Thursday AM, June 25, 1998

Session P. SiC Growth and Characterization

Room: 009
Location: Olsson Hall

Session Chairs: Larry B. Rowland, Sterling Semiconductor, Inc., Sterling, VA 20166-9535; Andrey Konstantinov, Industrial Microelectronics Center, Kista S-164 40 Sweden

8:20 AM, P1

Homoepitaxial 4H-SiC Growth on Substrates Misoriented Towards [-1100]: BARBARA E. LANDINI[1]; George R. Brandes[1]; [1]ATMI, 7 Commerce Drive, Danbury, CT 06810 USA

Substrate misorientation plays a critical role in determining SiC epilayer quality, but limited work has been done to examine the effect of miscut direction on 4H-SiC epilayers. To investigate substrate misorientation effects, 4H-SiC epilayers were grown on substrates miscut 4° and 8° either towards the [-1100] or the [11-20] crystalline direction. Epilayers up to 15 μm thick, possessing smooth morphologies free of macroscopic step bunching, were grown on substrates offcut 8° towards either the [-1100] or the [11-20] direction. Triangular defects were observed on epilayers grown on both substrate misorientations and were primarily located on the wafer periphery. The triangular defect density depended only on miscut angle and was larger on epilayers grown on 4° miscut substrates. AFM analysis confirmed the smooth surfaces for epilayers grown on both the [-1100] and the [11-20] miscut substrates. LEED studies of epilayers grown on substrates offcut towards [-1100] showed well defined spots and spot patterns characteristic of an ordered surface. N-type and p-type doping was achieved for epilayers grown on both substrate misorientations. Nitrogen doping levels were similar for epilayers grown using identical growth conditions on the two different 8° offcut directions, as measured using CV and SIMS analysis. N-type and p-type doping control via parameter variation was demonstrated for epilayers grown on substrates possessing both miscut directions.

8:40 AM, P2

Mechanisms of Homo- and Heteroepitaxial Growth of SiC On α-SiC(0001) by Solid-Source Molecular Beam Epitaxy: ANDREAS FISSEL[1]; Kay Pfennighaus[1]; Ute Kaiser[1]; Bernd Schroeter[1]; Wolfgang Richter[1]; [1]University of Jena, Institute of Solid State Physics, Max-Wien-Platz 1, Jena D-07743 Germany

SiC has attracted a considerable interest as potential material for high power and high temperature devices. In general, SiC epitaxial layers for such applications have been grown by means of chemical vapor deposition at high temperatures (T > 1600 °C). For future new applications, heteropolytypic or modulation-doped low-dimensional structures of SiC are expected to be of interest, too. Molecular beam epitaxy (MBE) is an attractive method to prepare such structures. First of all, however, conditions stabilizing the growth of certain polytypes have to be determined, which was not achieved by solid-source MBE so far. We report about growth mechanisms of homoepitaxial α-SiC and of heteroepitaxial 3C-SiC on α-SiC(0001) grown at temperatures between 115 0 and 1350 °C using solid-source MBE. However, the carbonization of the SiC surface is already a serious problem at these temperatures. At first, therefore, the boundary (equilibrium Si flux) for the inset of carbonization was determined from the occurrence of the C-determined (3x 3)R30° -superstructure in dependence on temperature. The obtained equilibrium Si vapor pressures correspond very well to those for the so-called SiC-C equilibrium, where the supersaturation is a strong function of the Si/C ratio also in the temperature range investigated. We have grown SiC films at conditions close to this equilibrium with rates in the range of 30 nm/h. Depending on substrate polytype, terrace length and supersaturation, the following growth modes were ob served: 1.Step-flow of already existing steps at temperatures T > 1200 °C and terrace length up to 1 μm on both 6H- and 4H-SiC. 2. Nucleation of 3C-SiC on terraces at higher supersaturation (σ>30). 3. Nucleation of 3C-SiC at defects, frequently observed on 4H-SiC at lower supersaturation (σ>10). 4. Homogeneous nucleation of 4H-SiC under conditions where the (3x 3)R30°-superstructure was observed during the deposition (more C-rich). Under this more C-rich conditions, the supersaturation (σ<10) corresponds well to a critical one for the 3C-SiC nucleation on 4H-SiC estimated from the differences in the surface energy and the chemical potential of 4H-SiC and strained 3C-SiC on 4H-SiC.

9:00 AM, P3

Extended Defects in SiC Epitaxial Layers Grown by Sublimation: ROSITZA YAKIMOVA[1]; Mikael Syväjärvi[1]; Erik Janzén[1]; [1]Linköping University, Dept. Physics and Measurement Technology, IFM, Physics House, Linköping S-581 83 Sweden

Silicon carbide epitaxial layers are the basis for a production of high power electronic devices. When very thick layers are required, the commonly used chemical vapor deposition method may become production limiting due to the relatively low growth rate. Sublimation epitaxy is a technique suitable for growth of SiC layers with a high growth rate (>100μm/hour), smooth surfaces and a high structural quality [1]. However, under some growth conditions morphological disturbances may occur. In this study extended defects in SiC epitaxial layers grown by sublimation epitaxy are investigated and discussed as to their appearance and formation mechanism. The results are considered in relation to the growth conditions. 6H and 4H-SiC epitaxial layers were grown on off oriented 6H (3.5°) and 4H (8°) SiC substrates, respectively at 1800-1900°C in a sublimation epitaxy set up described elsewhere [1]. Si-terminated surfaces were mainly utilized but for a comparison growth was performed on C-faces as well. Layer thicknesses up to 900μm were obtained with step flow growth mechanism. Besides as-grown surfaces, cross-sectional cleavages revealing the substrate-layer interface were investigated with a Nomarski interference optical microscope. To obtain additional information some of the samples were etched in molten KOH. The epitaxial layers are transparent with mirror-like surfaces. Occasionally extended defects may be observed under an optical microscope. Two types of such defects are found. A stripe defect is observed at an obstacle which is often a micropipe. This defect typically appears at growth rates exceeding 100μm/hour and might extend several mm in length along the step flow direction. From a cross-sectional view one can see that this defect is rather deep having clusters of stacking faults in the vicinity. Other

extended defects originate from some inclusions at the sample edge where the growth steps start and they follow the step propagation. It is shown by photoluminescence measurements that the inclusions contain 3C-SiC. These defects are shallow at the surface and have probably appeared close to the growth termination. The formation of the latter defects is discussed in relation to 2D nucleation while the former is related to step disturbances. [1] M.Syväjarvi, R.Yakimova. M.F.MacMillan, M.Tuominen, A.Kakanakova-Georgieva, C.Hemmingsson, I.G.Ivanov and E.Janzén, ICSCIII-N'97, Aug.31-Sept.5, 1997, Stockholm, Sweden

9:20 AM, P4

Electrical Properties of Ion-Irradiated Silicon Carbide: ANDREY O. KONSTANTINOV[1]; Anders Hallén[2]; [1]Industrial Microelectronics Center, Electrum-233, S-164 40 Kista Sweden; [2]Royal Institute of Technology, Department of Electronics, Electrum-229, S-164 40 Kista, Sweden

Ion-irradiated layers are commonly used in SiC device technology for device insulation and for termination of high voltage devices. Considerable improvement of device performance was reported by several groups, as well as problems related to large leakage currents at elevated voltages. In the present work we report on the first study of electrical properties of ion-irradiated silicon carbide. High energy iodine ions were implanted into commercially available bulk n-type 6H material with doses of 10^{14} and $2x10^{13}$ cm^{-2}. The choice of iodine was determined by a high ion mass, so as to obtain considerable damage with a relatively low dose. The ion energy was 15 MeV to ensure an ion penetration of about 3 μm. A high resistivity layer was formed at the surface upon irradiation. Metal contacts were deposited at room temperature onto the layer top to investigate electrical properties. The I-V curves were almost identical for both current directions, indicating that the current transport is controlled by the irradiated material itself rather than by a possible Schottky barrier at the metal-semiconductor interface. The conductance of irradiated material appears to be linear only for low applied voltages, below 10 V. At higher voltages the current exponentially increases with the voltage. The temperature and dose dependencies of low-field conductivity clearly point to the hopping mechanism of current transport. Semilog plots of conductance yield a characteristic $T^{0.25}$ dep endence on temperature, in agreement with the classical Mott's theory of hopping conductance. The material irradiated with a higher dose has a much higher conductance than that with a lower dose, which is again consistent with the hopping model of carrier transport. A lower amount of damage must result in a lower density of available hopping sites. The exponential high-field regime of the carrier transport could, in principle, be related to either space charge limited current flow or to the Pool-Frenkel effect. In our opinion the model of space charge-limited flow is more consistent with the experiment, particularly in view of the impurity band formation implied by the hopping low-field transport mechanism. The results of this study clearly demonstrate a close analogy between electrical properties of ion-irradiated silicon carbide and those of low temperature-grown gallium arsenide (LT GaAs). Both the low-field hopping-dominated conductance and the exponential high-field regime were indeed observed for LT GaAs. The latter is known to be a very useful tool for the performance improvement of GaAs microwave transistors: the operation voltage was in many cases increased by a factor of 2 to 3 using appropriate buffer layers of LT GaAs. With appropriate process control the ion beam modification technique can appear to be very helpful for obtaining increased power outputs from silicon carbide microwave devices.

9:40 AM, P5

Electrical and Optical Characterization of Vanadium in 4H and 6H-SiC: VALERIEA LAUER[1]; Gerard Guillot[1]; K. Chourou[3]; M. Anikin[3]; R. Madar[3]; Bernard Clerjaud[2]; [1]INSA Lyon, Laboratoire de Physique de la Matière (UMR-CNRS 5511), 20 Av.A.Einstein, Bâtiment 502, Villeurbanne, Rhône 69621 France; [2]Univeristé Pierre Et Marie Curie, Laboratoire d'optique Des Solides, Case Courrier 80, 4 Place Jussieu, Paris Cedx 05 75252 France; [3]Université Pierre Et Marie Curie, Laboratoire Des Matériaux Et Génie Physique, INPG, Rue DeLa Houille Blanche, Domaine Universitaire, Saint Martin d'Héres, Cedex 38402 France

Non intentionally vanadium doped 4H and 6H n type SiC grown by the Lely modified method have been investigated by electrical and optical measurements. Deep Level Transient Spectroscopy (DLTS) measurements on 6H-SiC reveal two levels which can be related to the vanadium acceptor state (V3+/V4+) in cubic site and hexagonal site at respectively Ec-0.68 eV and Ec-0.74 eV. On the other hand, one level was detected in 4H-SiC at Ec-0.85 eV and can be related also to the V3+/V4+ acceptor state. For the first time, we report Deep Level Optical Spectroscopy (DLOS) measurements on these deep levels. This characterization technique allows to measure unambiguously the photoionization cross section sn° (hn) of a level detected by DLTS in a wide range of energy. Spectra of the optical ionization cross section to the conduction band of a transition metal (TM) can then be interpreted as transitions towards the different minima of the conduction band and towards the TM excited states which can be near or resonant in the conduction band. The optical ionization cross sections of the levels detected by DLTS are well correlated with the shape of absorption spectra measured on the same materials. Owing to the internal transitions detected in the DLOS spectra, we confirm unambiguously the presence of the acceptor level (V3+/V4+) at Ec-0.68 eV and Ec-0.74 eV for the cubic and hexagonal sites respectively in 6H-SiC and at Ec-0.85 eV in 4H-SiC. In this last case, the energy separation between cubic and hexagonal sites is certainly too small to be detected by DLTS.

10:00 AM Break

10:20 AM, P6

Patterning of SiC Films Grown at Heteroepitaxial Temperatures on Si Substrates Using Microfabricated Molds: AAZZAM YASSEEN[1]; Christian A Zorman[1]; Mehran Mehregany[1]; [1]Case Western Reserve University, Microfabrication Laboratory, Department of Electrical Engineering and Applied Physics, 711 Glennan Building, Cleveland, OH 44106-7221 USA

Reactive ion etching (RIE) is a common method to pattern SiC films for microfabricated devices. Unfortunately, typical SiC etch rates are low when compared with other semiconductors like Si, due in part to the chemical inertness of SiC. Etch selectivities of SiC to Si and SiC to SiO_2 tend to be poor, especially for recipes with high etch rates. Common photoresists cannot withstand exposure to these plasmas, therefore masks made from Al and other materials are used. Aluminum has been linked to micromasking, which can result in undesirable features and roughening of etch fields. As an alternative to RIE, we have developed a micromolding technique which uses microfabricated SiO_2 molds in conjuction with mechanical polishing to pattern SiC films into micron-sized structures. The basic mold consists of a 1.5 μm thermally-grown SiO_2 film on a 4-inch diameter Si wafer. The SiO_2 mold is fabricated using well-established photolithographic and SiO_2 RIE techniques. Unmasked regions of the SiO_2 layer are completely etched to expose the underlying Si wafer. Using an APCVD process for heterepitaxial growth of 3C-SiC films on Si substrates, the SiO_2 molds are filled with SiC. SiC is grown on the exposed Si surfaces inside the mold and on the SiO_2 surfaces of the mold. In many locations, SiC does not adhere to the SiO_2 surfaces. In locations where the SiC film does adhere, mechanical polishing with a diamond-based slurry is used remove the film and expose the top surface of the mold. The mold is simply removed by dissolving the SiO_2 in an HF solution, which does not etch the SiC film or the Si substrate. The resultant structure is a patterned SiC film on a silicon substrate. We have used this technique to pattern SiC films into 5 mm-long lines with widths of 1, 2, 5, and 10 μm. The structural integrity of the features was preserved. Sharp edges, corners, and curves were nicely molded and delineated by this process. All features have smooth, nearly vertical sidewalls and very smooth top surfaces. We have also used this technique to create structural patterns for complex microelectromechanical devices, such as electrostatic resonators and micromotor gears. The overall thickness of a micromolded SiC film is limited, since the practical thickness of thermally-grown SiO2 is limited to about 3 μm. Unlike thermally-grown SiO_2, polysilicon can be deposited to much larger thicknesses (> 5 μm), can be deposited on many different substrate materials, and can be deposited at much lower temperatures (620°C), making it an attractive substitute, especially in multistep fabrication processes. We have used polysilicon molds to pattern SiC films grown at heteroepitaxial temperatures and the results will be presented in the extended paper.

10:40 AM, P7

Effect of Concentration on the Thermal Activation Energy of Nitrogen In 4H-SiC: WILLIAM C. MITCHEL[1]; Ronald Perrin[1]; Mohamed Ahoujja[1]; Andrew Evwaraye[2]; Steven R. Smith[3]; [1]Air Force Research Laboratory, Materials Directorate, AFRL/MLPO, 3005 P. St., Suite 6, W-PAFB, OH 45433-7707 USA; [2]University of Dayton, Department of Physics, 300 College Park, Dayton, OH 45469 USA; [3]University of Dayton Research Institute, 300 College Park, Dayton, OH 45469 USA

Activation energies of common donors and acceptors in semiconductors are important parameters for modeling transport and other electronic processes. Nitrogen is the most commonly used donor element is SiC and in the 4H polytype has two donor levels associated with substitutional atoms corresponding to the inequivalent hexagonal and cubic lattice sites. The thermal activation energies of the two levels have been studied by temperature dependent Hall effect and thermal admittance spectroscopy. Donor concentrations varied from below 10^{16} cm^{-3} to 10^{19} cm^{-3}. Hall effect measurements were made at temperatures up to 1000 K and the carrier concentration versus inverse temperature results were fitted to a multi-level charge balance equation using m* = 0.390, and Mc = 3, where m* is the electron effective mass and Mc is the number equivalent conduction band minima. This work extends the results of Götz et al.(1) who studied the activation energy of nitrogen in 4H by Hall effect in samples with concentrations between 5.1 and 70^{17} cm^{-3} to higher concentrations. In the lightest doped samples the two experiments gave the same values for the activation energies, E(d) = E(c) - 0.055 +/- 0.005 and E-(c) - 0.100 +/- 0.01 eV, in agreement with other reports. As the donor concentration increased both activation energies were found to decrease, activation energies as low as E(c) - 0.025 eV were observed. The activation energy was found to roughly agree with $E(d) = E(0) - aN(d)^{1/3}$. Thermal admittance spectroscopy was also used to study the conduction mechanisms in these samples. In addition to thermal activation of electrons from the nitrogen centers to the conduction band, we have observed two other activation energies, the e(3) for hopping conduction as well as e(2) for conduction from neutral to neutral centers. In addition to the three activation energies, emission rates for these processes will also be reported. The concentration dependence of E(d) from TAS is similar to that observed from Hall effect measurements. Similar dependences of activation energy on doping concentration have been observed in other semiconductors and are most often attributed to a broadening of the impurity level and a merging of the excited states with the conduction band.(2)1. W. Götz, A. Schöner, G. Pensl, W. Suttrop, W. J. Choyke, R. Stein, and S. Leibenzeder, J. Appl. Phys. 73, 3332 (1993). 2. J. S. Blakemore, Semiconductor Statistics (Pergamon, New York, 1962) pg. 166.

11:00 AM, P8

Dielectric Function of Bulk 4H and 6H and Epitaxial 3C SiC on Si: STEFAN ZOLLNER[1]; Jiangang Gordon Chen[1]; James N. Hilfiker[2]; John A. Woollam[3]; T. E. Tiwald[3]; [1]Motorola Semiconductor Technology, Arizona Technology Laboratories, Technology Test and Analysis Laboratory, MD M360, 2200 West Broadway Road, Mesa, AZ 85202 USA; [2]J. A. Woollam Co., Inc., 645 M Street, Suite 102, Lincoln, NE 68505 USA; [3]University of Nebraska, Lincoln, Center for Microelectronic and Optical Materials Research, Electrical Engineering, 209N WSEC, Lincoln, NE 68588 USA

Spectroscopic ellipsometry was used to measure the dielectric function of bulk 4H and 6H SiC from 0.73 to 6.58 eV for light propagating nearly parallel to the hexagonal axis. Accurate data for both ε_1 and ε_2 could be obtained through the use of an autoretarder, which overcomes the difficulty of rotating-analyzer ellipsometry to study materials with low absorption coefficients. The data were corrected for a SiO_2 (or surface roughness) overlayer with a thickness of about 1.5 nm to achieve an ε_2 of zero below the indirect gap. Our data are almost identical to results for cubic (3C) and 6H SiC from the literature at low photon energies, but differences are notable above 4 eV. These data can be used for metrology applications in microelectronics, such as monitoring oxidation of SiC for high-power devices. In 4H SiC, we observe a critical point at 5.55 eV, which is assigned to direct interband transitions along the U=M-L axis in the hexagonal Brillouin zone after comparison with band structure calculations. The critical-point parameters (energy, broadening, amplitude, and phase angle) were determined in comparison with analytical lineshapes. No evidence for direct transitions below 6.5 eV was found in 6H SiC. For comparison, we also studied a 1 γm thick epitaxial layer of cubic (3C) SiC on Si from Case Western Reserve University. This sample exhibits strong interference oscillations below the onset of absorption. With the autoretarder, we are able to determine the sign of the ellipsometric angle Δ (and thus also that of the imaginary part of the pseudodielectric function). Analysis of these data indicates a surface roughness of 10 nm (verified by atomic force microscopy, which finds an rms roughness of 14 nm) and an interface roughness of 21 nm thickness. The interface roughness originates from a highly defective layer at the interface (stacking faults, misfit dislocations, twins, voids, etc.). Because of the surface roughness, we were unable to determine the optical constants of 3C SiC. However, we find a critical point at 5.95 eV, which is caused by optical interband transitions from the X_5 valence band to the X_1 (or X_3) conduction band, i.e., $E_2(X)$.

11:20 AM, P9
Late News

11:40 AM, P10
Late News

Thursday AM, June 25, 1998

Session Q. IR Materials and Devices I

Room: 011
Location: Olsson Hall

Session Chairs: Robert A. Biefeld, Sandia National Labs, Albuquerque, NM 87185-0601; Andrew D. Johnson, DERA, Great Malvern, WR14 3PS UK; Richard H. Miles, SDL, Inc. San Jose, CA 95134-1365

8:20 AM, Q1

Processing and Characterization of Antimonide Mid-IR Diode and Interband Cascade Lasers: EDWARD H. AIFER[1]; Linda J. Olafsen[1]; William W. Bewley[1]; Christopher L. Felix[1]; Igor Vurgaftman[1]; JERRY R. MEYER[1]; D. Zhang[2]; C.-H Lin[2]; S. S. Pei[2]; [1]Naval Research Laboratory, Optical Sciences Division, Code 5613, 4555 Overlook Ave SW, Washington, DC 20375 USA; [2]University of Houston, Space Vacuum Epitaxy Center, Houston, TX 77204 USA

We describe the fabrication and performance characterization of electrically-pumped mid-IR lasers based on strained-layer type-II antimonide quantum wells grown by MBE. Wet etching "brings out" wafer defects such as strain dislocations and pits, resulting in poor surface morphology that degrades subsequent processing steps. Furthermore, the presence of AlSb layers thicker than about 100 nm results in exceedingly poor wet-etch characteristics, due to the rapid oxidation of any exposed layers in air or water. Device definition, uniformity, and reproducibility are improved when the wet etch is replaced by reactive-ion-etching (RIE) using Ar/BCl_3. The devices employ silicon nitride passivation and Ti/Pt/Au non-alloyed ohmic contacts. Both gain-guided and mesa-isolated stripe lasers were fabricated. For the interband cascade configuration with relatively high input impedance, mesa isolation eliminated the significant increase in threshold due to current spreading. However, permanent damage in the form of electrical shorting also occurred more readily in the mesa-isolated lasers. A 2.9-micron diode laser with a type-II superlattice active region was found to lase at temperatures up to 260 K. At all T > 180 K, thresholds were lower than for any previously-reported semiconductor laser in this wavelength range, e.g., only 1.1 kA/cm^2 at T = 200 K. The peak power per facet was more than 0.8 W at 100 K and 0.2 W at 200 K. The interband cascade laser (ICL) is a recently-demonstrated new approach that is similar to the quantum cascade laser, except that the rapid non-radiative phonon relaxation associated with intersubband processes is eliminated through the use of interband active transitions. A separate photon is generated at each period of the active region as electrons cascade down a staircase-like structure. Here we will report characterization results for a pulsed ICL (λ = 3.5 microns) which operated nearly to room temperature. The T_{max} of 286 K exceeded the previous record for interband III-V diodes emitting at $\lambda \oplus$ 3.3 microns by more than 60 K. Both the maximum operating temperature and the peak power of 160 mW/facet at 196 K were limited by the onset of permanent damage rather than by any constraints intrinsic to the device (such as heating). The slope efficiency at 196 K was 197 mW/A per facet, which corresponds to the emission of 1.1 photons per injected electron.

8:40 AM, Q2

The Determination of Radiative and Non-Radiative Recombination Mechanisms In P-InAs From AlAsSb/InAs Heterojunction Light Emitting Diodes: MICHAEL JOHN KANE[1]; Trevor Martin[1]; Glyn Braithwaite[1]; Martin Emeny[1]; David Lee[1]; David Wight[1]; [1]Defence Evaluation and Research Agency, Electronics Sector, Room PA123, St Andrews Road, Malvern, Worcestershire WR14 3PS United Kingdom

Light emitting diodes (LEDs) working in the mid infrared (2-5 μm wavelength) are of increasing interest in applications such as chemical and environmental sensing. The light generation efficiency of such LEDs is generally much less than equivalent devices in the near infrared (λ<1 μm). There is little published analysis of why this is so. This paper presents a study of InAs p-n homojunction LEDs (λ_{peak}~3.4 μm) with a p-InAs active region. Experimental data and analysis are presented that show that the radiative recombination efficiency of the active material can be close to unity at low injection but that the internal efficiency of the LED can be much lower than this because of surface recombination, re-absorption and high injection effects. (This first effect is shown to be strong in mid infrared LEDs because of the long minority electron diffusion lengths associated with the small band gap.) The diodes incorporate a p-InAs/p-AlAsSb heterojunction to suppress surface recombination. The interface recombination velocity at the AlAsSb/InAs interface is shown to be ~$1.5x10^4$ cms^{-1} from an analysis of the dependence of the LED efficiency on the distance of this interface from the InAs p-n junction. This value of interface recombination velocity is then used to determine the internal efficiency of the p-InAs. The presence of an interface with a known and minimized recombination velocity is shown to be essential for the determination of the internal efficiency of p-InAs with a hole concentration <~ $5x10^{17}$ cm^{-3}. The p-InAs active material (MBE grown with Be dopant) is shown to have a low-injection radiative efficiency which decreases with increasing hole concentration in a manner consistent with the dominant non radiative processes being the Auger processes that have two holes in their initial state, the CHHL and CHHS processes. The combined rate constant for these Auger processes is found to be $2x10^{-28}$ cm^6s^{-1}. There are no previous experimental determinations of this value. The low doping limit of the radiative efficiency is 0.27. This is ascribed to recombination via defects. Under increasing injection a non thermal decrease in radiative efficiency of p-InAs is also observed. The strength of this effect is consistent the dominant high injection non radiative effect being the CCHC Auger process with a rate constant of 1-$2x10^{-26}$ cm^6s^{-1}. This rate constant is consistent with previous experimental work. The difference in rate constants between the CCHC Auger processes and the CHHL and CHHS processes means that the CCHC process always the dominates in the high injection regime. This abstract is intended for the symposium on infrared materials and devices.

9:00 AM, Q3

Calculated and Measured Carrier Recombination in Mid-Infrared Semiconductor Heterostructures: MICHAEL E. FLATTE[1]; J. T. Olesberg[1]; S. A. Anson[1]; D. -J. Jang[1]; T. C. Hasenberg[1]; Thomas F. Boggess[1]; C. H. Grein[2]; [1]The University of Iowa, Department of Physics and Astronomy, 100 IATL, Iowa City, IA 52242 USA; [2]The University of Illinois, Department of Physics, 845 W. Taylor Street, #2236, Chicago, IL 60607 USA

Nonradiative carrier recombination is a key factor limiting the maximum operating temperature of mid-infrared semiconductor lasers. At room temperature, the primary nonradiative process is Auger recombination, in which the energy released by the recombination of an electron-hole pair is used to promote another carrier to a higher energy. Much work has gone into designing mid-infrared materials in which Auger recombination is suppressed. We compare experimental measurements and theoretical calculations of Auger recombination rates in mid-infrared heterostructures grown by molecular beam epitaxy on GaSb substrates. Measurements and calculations were performed to determine Auger rates as a function of temperature and carrier density. Measurements of the Auger rate were performed using two all-optical techniques: time-resolved differential transmission and time-resolved photoluminescence upconversion, both of which have sub-picosecond temporal resolution. Detailed measurements were performed on a 4 micron band gap broken-gap superlattice whose repeating unit cell consists of layers of InAs/GaInSb/InAs/AlGaInAsSb. The measurements indicate a Shockley-Read-Hall lifetime of 2.7 ns at all temperatures. At low excitation densities, the observed Auger rate per carrier increases with density as N^2. However, at densities where the valence band becomes degenerate, the Auger rate saturates to a linear density dependence. This indicates that the dominant Auger process involves promoting a hole in the valence band rather than an electron in the conduction band. At low densities, the measured room temperature Auger coefficient is $2.5x10^{-27}$ cm^6 s^{-1}. Measurements performed as a function of temperature show that the Auger rate for a given density increases with temperature. Calculations of the Auger rate were performed using the non-parabolic band structure and momentum dependent scattering matrix elements generated from a superlattice K.p formalism. The calculated Auger rates show exceptional agreement with the measurements; the calculations reproduce both the magnitude and the density dependence of the Auger rate, including the transition to sub-quadratic density dependence. The calculations reveal the importance of including growth-direction Umklapp processes in the calculation of carrier lifetimes for repeating structures (multiple quantum wells or superlattices) whose growth-direction unit cell is longer than 30 angstroms. Neglect of Umklapp processes in the calculation of Auger rates in our 4 micron band gap structure leads to an underestimation of the rate by more than a factor of two. The excellent agreement between measured and calculated rates implies that the calculations and the model of the electronic structure on which they are based are sufficiently accurate to be used in the optimization of mid-infrared laser active regions.

9:20 AM, Q4

Electronic and Optical Properties of InAsSb/InAsP Strained-Layer Superlattices and Constituent Alloys: STEVEN R. KURTZ[1]; A. A. Allerman[1]; R. M. Biefeld[1]; [1]Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-0603 USA

InAsSb/InAsP strained-layer superlattices (SLSs) have been developed as active regions for mid-infrared lasers and LEDs. These superlattices offer improved hole confinement over earlier InAsSb/InAs or InAsSb/InGaAs heterostructures, and a miscibility gap, reported with InAsSb/InAlAsSb SLSs, has not been encountered in SLSs with InAsP barriers. High quality SLSs, lattice-matched to the InAs substrate, display photoluminescence energies spanning the 3.5-5.0 μm range at low temperature (4.2 - 5.8 μm at 300 K). Similar to the InAsSb/InAs and InAsSb/InGaAs heterostructures, we find that the InAsSb/InAsP SLSs have type I band offsets. Magneto-photoluminescence studies of the SLS reveal an electron-hole reduced mass lower than that observed in InAs or InAsSb bulk alloys due to the light in -plane mass of the hole state in the compressively strained InAsSb layer. Magneto-photoconductivity measurements display n=0 - 5 Landau states originating from a ($|e,\pm1/2\rangle$ - $|3/2,\pm3/2\rangle$) transition at the band-edge. Unlike other InAsSb alloys and heterostructures that we have studied magneto-optically, additional transitions are not resolved. Carrier confinement of InAsSb/InAsP quantum wells supported high efficiency, "cascaded" laser operation. 10-stage, InAsSb/InAsP lasers operated at 3.8-3.9 μm up to 180 K. At 80 K, peak laser power > 100 mW and a slope-efficiency of 48% (4.8% per stage) were observed. Slope-efficiency was strongly dependent on cavity length, and analysis of efficiency data suggest an internal quantum efficiency > 1 and a loss coefficient * 100/cm at 80 K. We attribute the large loss at 80 K to optical absorption by free carriers in semi-metal injection layers.

9:40 AM, Q5

MBE Grown InAlSb/InSb Quantum Well Mid-Infrared Diode Lasers: GRAHAM JOHN PRYCE[1]; Tim Ashley[1]; Mark Carroll[2]; Thomas Elliott[1]; Richard Jefferies[1]; Andrew David Johnson[1]; Ben Murdin[3]; [1]DERA, Nanotechnology Department, K2002, St. Andrews Road, Malvern, Worcestershire WR14 3PS UK; [2]University of Wales College of Cardiff, Department of Physics, Cardiff, Wales CF2 3YB UK; [3]University of Surrey, Department of Physics, Guildford, Surrey GU2 5XH UK

We have been developing mid-infrared emitters, with peak wavelengths in the range from 3.5μm to 6μm. These devices have potential use in the areas of remote detection of pollutant and toxic gases, general spectroscopy, eye-safe range finding and secure communications. We have previously demonstrated InSb and InAlSb LEDs operating uncooled, InSb lasers which operate up to 100K, giving 28mW per facet at 80K, and InAlSb lasers operating up to 155K. We now report InAlSb/InSb multi-quantum well laser devices, grown in order to investigate the potential benefit of these structures for reducing Auger recombination and intervalence absorption effects. The devices were grown by MBE onto InSb(001) substrates, and are therefore not lattice matched. The diodes are a psuedo double heterostructure, comprising an undoped active region 2μm thick, consisting of 121 repeats of $In_{0.904}Al_{0.096}Sb$/InSb (10nm/6.5nm), surrounded by 0.5μm thick layers of $In_{0.942}Al_{0.058}Sb$. A wider band gap layer (20nm thick) of $In_{0.793}Al_{0.207}Sb$ is incorporated on the p-type side of the diode, which provides a barrier in the conduction band to electron flow from the active region, thus giving good electrical confinement. Highly doped n-type InAlSb layers surround the

active region, confining the optical mode (with a confinement factor of ~98%), due to a Moss-Burstein shift of refractive index. The devices are a wet etched mesa structure typically 100μm wide, being cleaved to form facets 500μm apart. A CrAu contact overlays an insulating SiO_2 layer and makes contact to the top n-type side, via a window in the SiO_2. Connection is made to the substrate via a solder contact. FTIR spectroscopy measurements revealed a lasing wavelength of 3.76μm at 80K. The stimulated peak bandwidth was $<1cm^{-1}$, this being the spectrometer resolution. The emission spectrum had a single peak just above threshold, however, far above threshold, the spectrum was multi-modal with a spacing consistent with a 500μm long Fabry-Perot cavity. Under pulse bias conditions at 80K, the threshold current density was $240Acm^{-2}$. The output power was 100mW per facet at $2kAcm^{-2}$. The average differential quantum efficiency up to $400Acm^{-2}$ is 50%. We have demonstrated stimulated emission up to 130K, with a characteristic temperature of 18K, at which point the threshold current density was $3.7kAcm^{-2}$, and the peak wavelength was 3.82μm.

10:00 AM Break

10:20 AM, Q6

The Growth of Improved Mid-Infrared InAsSb Emitters by Metal-Organic Chemical Vapor Deposition: R. M. BIEFELD[1]; A. A. Allerman[1]; K. C. Baucom[1]; S. R. Kurtz[1]; [1]Sandia National Laboratory, Dept. 1113, MS 0601, PO Box 5800, Albuquerque, NM 87185 USA

We report on recent progress and improvements in the metal-organic chemical vapor deposition (MOCVD) of mid-infrared (3-6 μm) emitters. Lasers and LEDs are being developed for use in chemical sensor systems and infrared countermeasure technologies. We have demonstrated improved performance for midwave infrared emitters in strained InAsSb/InAs and InAsSb/InAsP heterostructures. The addition of P to the InAs barriers increases the light and heavy hole splitting and hence reduces non-radiative Auger recombination and provides for better electron and hole confinement in the InAsSb quantum well. To further improve laser and LED performance, we are exploring the MOCVD-growth of novel multi-stage (or cascaded) active regions in InAsSb-based devices. These devices use AlAsSb claddings and strained InAsSb/InAsP active regions. A semi-metal GaAsSb/InAs layer acts as an internal electron source for the multi-stage injection lasers and AlAsSb is an electron confinement layer. The structures were grown using a high speed rotating disk reactor (RDR). Growth in an RDR was necessary to avoid the previously observed Al memory effects found in conventional horizontal reactors. A semi-metal GaAsSb/InAs layer acts as an internal electron source for the multi-stage injection lasers and AlAsSb is the electron confinement layer. These multi-stage structures are the first cascaded devices grown by MOCVD. Interaction between some of the sources, such as trimethylindium and trimethylamine alane, caused graded interfaces that prevented device operation. We will report the optimized growth conditions, including purging sequences, that were necessary to grow operating devices. Multi-stage LEDs have been fabricated which exhibit an average power at room temperature of > 100 μW at 4.μm. Lasers have also been demonstrated. The growth of further refined structures is being explored and results on these devices will also be presented.

10:40 AM, Q7

Optical Performance and Structural Characterization of 2 μm GaInAsSb/AlGaAsSb: A. L. GRAY[1]; T. C. Newell[1]; S. Dorato[1]; L. F. Lester[1]; [1]University of New Mexico, 1313 Goddard SE, Albuquerque, NM 87106 USA

Accurate knowledge of the composition, strain, and thickness of GaInAsSb/AlGaAsSb multi-quantum wells (MQW) on an atomic scale is critical for correlating device performance of mid-infrared (2-5 μm) semiconductor lasers with specific material designs. However, device results are often obtained without detailed information of these structural parameters because they are very difficult to measure in Sb-based quaternaries. For example, the normal technique of extracting thickness and composition from photoluminescence data is not possible given the uncertainty in the energy band offsets and effective masses. The objective of this paper is to describe a novel method for the structural characterization of GaInAsSb/AlGaAsSb MQW laser structures grown by molecular beam epitaxy (MBE) and designed for 2 μm operation. In addition, the state-of-the-art optical performance of these 2 μm lasers is presented. The devices exhibit a characteristic temperature, TO = 140 K, and differential efficiencies as high as 74% at 25ϒC. The TO value is the highest reported for any laser with a wavelength longer than 1.5 μm and is significantly greater than that reported for 2 μm wavelength phosphide-based lasers. Threshold current densities as low as 174 A/cm^2 and 225 A/cm^2 are measured for 2- and 4-QW lasers, respectively. High-resolution x-ray diffractometry (HRXRD) in conjunction with transmission electron microscopy (TEM) is employed to characterize a compressively strained AlGaAsSb/GaInAsSb MQW laser structure. From a theoretical point of view, it is possible to determine the compositions and thicknesses in the MQW by interpreting the pendellosung fringes of the x-ray spectra if the barrier composition is known, but from a practical standpoint, the insensitivity of the fringe intensity to compositional changes requires the use of a second, independent measurement such as TEM. The barrier composition, nominally the same as the waveguide core composition, is determined from the unique x-ray peak of the thick waveguide region. Finally, by comparing the spacings and intensities of the pendellosung fringes and the entire MQW thickness as determined by TEM with a dynamical diffraction theory simulation, the well and barrier thicknesses, well composition, and strain are unambiguously determined. The values for the well and barrier thicknesses are 105 and 108 angstroms, respectively, for the $In_{0.15}Ga_{0.85}As_{0.06}Sb_{0.94}$ wells yielding a strain of 0.51%. Using this data, it is shown that our theoretical model for the GaInAsSb/AlGaAsSb QW energy transitions closely predicts the lasing wavelength of the devices reported here and lends credibility to the energy offset and effective mass values used in the model. 1. M.G. Young, S.A. Keo, S. Forouhar, T. Turner, L. Davis, R. Mueller, and P.D. Maker: Room Temperature InGaAs-InGaAsP distributed feedback operating beyond 2 μm, Proc. LEOS '97, San Francisco, CA, November 1997, pp. 73-74.

11:00 AM, Q8

Variation of the Threshold Current and Differential Efficiency in Bulk, Antimonide Based Laser Diodes Under Application of High Magnetic Fields: B. N. MURDIN[1]; R. Kotitschke[1]; A. Hollingworth[1]; M. Kamal-Saadi[1]; E. O. Reilly[1]; A. R. Adams[1]; P. Findlay[2]; C. R. Pidgeon[2]; C. J.G.M. Langerak[3]; T. Ashley[4]; G. Pryce[4]; C. T. Elliott[4]; [1]University of Surrey, Dept. of Physics, Guildford, GU2 5XH UK; [2]Heriot Watt University, Dept. of Physics, EH14 4AS, Edinburgh UK; [3]FOM, Institute for Plasma Physics, Rijnhuizen, P.O.Box 1207, NL-3430 BE Niewegein, The Netherlands; [4]DERA, St. Andrews Road, Malvern, Worcs WR14 3PS, UK

One of the primary processes governing the maximum device operating temperature in interband semiconductor lasers for the mid-infrared region of the spectrum is Auger recombination. This process normally has a lower threshold for narrow bandgap materials, and is enhanced by the typically large intrinsic carrier concentrations at room temperature. One possible way to suppress this recombination channel is the use of low dimensional structures, such as quantum wires and dots, which may incertain circumstances lead to a reduction in the density of states at the Auger threshold energy. States with a high transition probabilitythus have a low DOS and vice versa. At the same time, reduction of the DOS away from the lasing states may lead to a reduction in the threshold carrier density. We present results of laser characterization under the application of high magnetic fields. The effect of the magnetic field is quantize the charge motion in the plane perpendicular to the field, and thus to mimic a quantum wire-like potential. An added benefit is that the length scale of the quantization is tuneable with the field. The lasers used were bulk devices with active layers of InAlSb with Al-fractions of 0 or 5.2%, grown by MBE on [111] InSb substrates. The devices were mounted in the bore of a superconducting magnet and the lasing threshold at various temperatures was measured, with the B-field either parallel or perpendicular to the growth axis. The magnetic field caused a significant drop in the threshold current, by as much as 30%, up to 3 tesla. Thereafter the threshold either rose or stayed constant depending on the temperature and orientation. It seems likely that the initial benefits of the magnetic quantization are overcome by the field induced increase in the DOS at the lasing energy (the DOS at the band edge is not size dependent in a real well, wire or dot). Also seen in conjunction with this effect is a dramatic reduction in the differential efficiency, which is the reverse of what would be expected for a sharply peaked DOS. This might be explained by the phononbottleneck effect, which slows electron cooling to the bottom of the band, and whose lifetime would depend on the degree of quantization. The effects of the field on the electrical and optical leakage into the cladding will also be discussed.

11:20 AM, Q9

GaAs/AlGaAs Quantum Cascade Emitter: GOTTFRIED STRASSER[1]; Stefan Gianordoli[1]; Lubos Hvozdara[1]; Karl Unterrainer[1]; Erich Gornik[1]; [1]TU Vienna, Solid State Electronics, Floragasse 7, Vienna 1040 Austria

The development of the quantum cascade laser [1] in 1994 has marked a breakthrough in the application of intersubband transitions. All results so far were achieved within a single material system, namely InGaAs/InAlAs lattice matched to InP. In the GaAs/AlGaAs material system intersubband photoluminescence, stimulated emission and finally lasing in the long wavelength range was achieved by optical pumping with a free electron or a CO_2 laser [2]. Electrically pumped GaAs/AlGaAs intersubband luminescence at cryogenic temperatures was demonstrated by Li et al. [3] and by our group [4], room temperature electroluminescence of a QCL-structure was reported by us recently [5]. For an electrical pumped laser the realization of the waveguide cladding layers has to be considered carefully, since, in contrast to the InGaAs/InAlAs/InP system, the substrate material has the smallest energy gap and largest refractive index and, thus, cannot be used as a lower cladding layer. In addition, AlGaAs with high Al-content has deep-lying donor states (DX centers), which give rise to inferior transport properties and could therefore induce a large series resistance. We report on the design, growth and characterization of intersubband quantum well structures based on the GaAs/AlGaAs material system. A GaAs/AlGaAs intersubband LED designed to emit radiation at 7 micron shows intersubband emission at a wavelength of 6.9 micron up to room temperature with linewidths (FWHM) of 14 meV at 10 K and 20 meV at 300 K. Due to mode profile and waveguide loss calculations, total growth thickness of real laser structures are close to the 10 micron thickness range and therefore challenging from the MBE growth point of view. Our first attempts to fabricate an electrically pumped laser structure based on these devices encountered difficulties with the electrical properties of the AlGaAs waveguide cladding layers. Thus, we present calculations and measurements with different waveguide concepts as doped GaAlAs cladding layers and doped superlattice cladding structures as well as disk lasers. Newest results on our attempts to fabricate a GaAs/AlGaAs quantum cascade laser with a wavelength of 10 micron will be presented (transport behavior, infrared absorption, photocurrent spectra, and electroluminescence data). [1] J. Faist et al., Science 264, 553 (1994) [2] S. Sauvage et al., Appl. Phys. Lett. 70, 1345 (1997); O. Gauthier-Lafaye et al., Appl. Phys. Lett. 70 (24), 3197 (1997); O. Gauthier-Lafaye et al., Appl. Phys. Lett., in print [3] Y.B. Li, et al., Electron. Lett. 33, 1874 (1997) [4] G. Strasser et al., Appl. Phys. Lett. 71 (20), 2892 (1997)[5] P. Kruck et al., Proc. MSS8, Santa Barbara (1997), Physica B, in print

11:40 AM, Q10+

Mid-Infrared GaAs/AlGaAs Based Quantum Cascade Emitters: BENJAMIN S. WILLIAMS[1]; Brian Riely[1]; Qing Hu[1]; MICHAEL R. MELLOCH[2]; [1]Massachusetts Institute of Technology, Dept. of Electrical Engineering and Computer Science, 77 Massachusetts Avenue, 26-461, Cambridge, MA 02139 USA; [2]Purdue University, School of Electrical and Computer Engineering, 1285 Electrical Engineering Bldg., West Lafayette, IN USA

We are currently developing mid-infrared (8-12 micron) quantum cascade lasers based on GaAs/AlGaAs heterostructures. A compact, tunable, room temperature laser in this atmospheric transmission window would be extremely useful for remote chemical sensing and pollution monitoring. The GaAs/AlGaAs material system holds promise for improved high temperature performance over current InGaAs/InAlAs quantum cascade lasers due to the higher thermal conductivity of the binary alloy. We have designed an electrically pumped multiple quantum well (MQW) structure to produce infrared emission based on unipolar intrawell intersubband transitions. Under proper bias, population inversion between the two subbands is established by fast LO-phonon scattering to depopulate the lower subband. Also, a superlattice Bragg reflector confines electrons to the upper subband, while allowing rapid tunneling out of the lower subband. Carriers are supplied by setback doping in the superlattice region. Setback doping and the intrawell transition design reduce linewidth broadening due to impurity scattering and interface roughness scattering, respectively. Our design incorporates 40 such modules cascaded together. Electroluminescence has been observed from edge emitting mesa structures at 10 K. Microwatt intersubband emission power levels were measured for 66 micron wide edge emitting mesas with 1 A current pulses (5 kA cm^{-2}). We have resolved the spontaneous emission using Fourier transform infrared spectroscopy. A narrow (11 meV) emission peak was observed at the design energy of 120 meV (λ = 10.3 microns). Prospects are good for achieving lasing when this MQW structure is placed in the appropriate cavity. Two such cavities are being investigated for their suitability. Radiation confinement above the MQWs is provided by deposited metal for the contact. Plasma confinement due to heavily doped GaAs layers can be used below the multiple quantum wells. However, such confinement is somewhat lossy due to free carrier absorption. A novel metallic waveguide has been developed to improve mode confinement and reduce free carrier cavity losses by eliminating the need for thick heavily doped layers. Such a waveguide will lower the lasing threshold and will permit operation at higher temperatures.

Thursday AM, June 25, 1998

Session R. Defects and Device Reliability

Room: 120
Location: Olsson Hall

Session Chairs: Steve Stockman, Hewlett-Packard Optoelectronics Divison, San Jose, CA 95131 USA; Steve Ringel, Ohio State University, Dept. of Electrical Engineering, Columbus, OH 43210 USA

8:20 AM, R1+

Misfit Dislocation-Induced Strain Relaxation and Lattice Tilt in In GaP/GaAs/Ge Solar Cells: R. R. HESS[1]; M. S. Goorsky[1]; [1]UCLA, Materials Science and Engineering, 405 Hilgard Ave., 6531 Boelter Hall, Los Angeles, CA 90095-1595 USA

Space-based compound semiconductor solar cells require Ge substrates which are highly miscut to minimize antiphase boundary formation. Misfit dislocation formation is strongly influenced by the substrate miscut angle and miscut direction as has been previously demonstrated for simple heterostructures but this phenomenon has not been extensively studied in device structures. Here, we examined the role of a 9° Ge substrate miscut (with the miscut direction 26° away from a <110> direction) on misfit dislocation formation in InGaP / GaAs / Ge tandem junction solar cells. The » 4 μm GaAs buffer layer is relaxed by about 85% compared to the Ge substrate as determined by triple axis x-ray diffraction. The GaAs layer is also tilted by 60 arcsec in the same direction as the Ge substrate miscut and the miscut is rotated by 15° about the substrate miscut direction. The 15° rotation derives from both the polar / nonpolar interface and because the miscut direction is not along a high-symmetry direction although the observed magnitude of the tilt is not predicted by most common models. The tilt in the GaAs buffer acts to make the <110> step ledges more symmetric and moves the 9° (+ 60 arcsec) miscut towards a major crystallographic axis. Subsequently grown $Al_{0.65}Ga_{0.35}As$ and $In_{0.514}Ga_{0.486}P$ device layers are pseudomorphic with respect to the GaAs buffer layer and exhibit the expected pseudomorphic layer tilting of 58 arcsec and 125 arcsec, respectively with respect to the GaAs substrate. There is no rotation (as expected) of the epitaxial strained layers with respect to the GaAs buffer layer.

8:40 AM, R2+

Deep Level Defects in MOCVD-Grown $In_xGa_{(1-x)}As_{(1-y)}N_y$ Layers Lattice-Matched To GaAs: ROBERT JAMES KAPLAR[1]; John J Boeckl[1]; Daewon Kwon[1]; Steven A Ringel[1]; H Q Hou[2]; B E Hammons[2]; [1]Ohio State University, Electrical Engineering, 205 Dreese Lab, 2015 Neil Avenue, Columbus, OH 43210 USA; [2]Sandia National Laboratories, Albuquerque, New Mexico 87185 USA

Current high-efficiency tandem-junction space solar cells typically consist of 3 lattice-matched homojunctions based on $In_{0.5}Ga_{0.5}P$, GaAs and Ge, with respective bandgaps of 1.85, 1.42 and 0.67 eV, epitaxially grown on Ge substrates. While air mass zero (AMO) conversion efficiencies over 25% have been demonstrated with this cell, the large energy difference (0.75 eV) between the GaAs and Ge bandgaps represents a major efficiency loss mechanism inherent in this design, in which energy exceeding the Ge bandgap (but less than GaAs) is lost as heat to the Ge cell. Hence, insertion of a fourth cell with a bandgap between Ge and GaAs will minimize this loss and should increase efficiency dramatically. This desire has motivated significant, recent interest in the quaternary $In_xGa_{1-x}As_{1-y}N_y$ alloy as a candidate material for this application. By incorporating small amounts of N and maintaining a compositional relation of

x ~ 3y, $In_xGa_{1-x}As_{1-y}N_y$ can be grown lattice-matched to GaAs or Ge substrates while providing bandgaps between 0.67 eV and 1.42 eV. Simulations show that an optimal 4-cell tandem design requires an InGaAsN junction with a bandgap of 1.05 eV between the GaAs and Ge cells. With such a configuration, theoretical AMO efficiencies over 40% are projected. However, growth of this quaternary material is challenging, and the dependence of optoelectronic properties on growth conditions and alloy composition must be explored. An important aspect of this is deep level defect introduction, which impacts transport properties and material quality. Here we present the first study of deep levels within this quaternary nitride and investigate overall material quality as a function of alloy composition within the lattice-matched range on GaAs substrates. $In_xGa_{1-x}As_{1-y}N_y$ layers were grown by MOCVD on GaAs substrates. Growth of $In_{.045}Ga_{.955}As_{.985}N_{.015}$ was confirmed by SIMS, and optical absorption measurements revealed a sharp absorption edge (bandgap) at 1.05 eV for this composition. X-ray rocking curve measurements showed these films to be lattice-matched to the underlying GaAs and of excellent crystallinity. P and n-type doping were achieved in the range of $1x10^{16}$ to $5x10^{18}$ cm^{-3} using C and Si as dopants, respectively, and this was used to grow and fabricate InGaAsN pn junctions for deep level transient spectroscopy (DLTS) measurements. DLTS consistently revealed 3 electron traps within n-type InGaAsN layers, with activation energies of 0.147, 0.246 and 0.537 eV. The 0.147 eV level dominates the trapping spectrum, and filling pulse time experiments to explore the capture kinetics indicate asymmetric DLTS peak broadening suggestive of an extended defect origin for this level. In contrast, the other two traps follow ideal point defect behavior. Minority carrier injection DLTS does not reveal additional hole traps within the n-InGaAsN. Potential physical sources for these various states and trapping behavior will be discussed in greater detail and the effect of alloy composition will also be explored. Correlations with diode characteristics will be presented.

9:00 AM, R3

Cathodoluminescence Spectroscopy of Deep Defect Levels at the ZnSe/GaAs Interface With A Controlled Interfacial Layer: J. SCHAEFER[1]; A. P. Young[2]; T. M. Levin[2]; L. J. Brillson[1]; L. Vanzetti[3]; A. Bonanni[3]; A. Franciosi[3]; [1]Ohio State University, Center for Materials Research, 2015 Neil Avenue, Columbus, OH 43210 USA; [2]Ohio State University, Department of Electrical Engineering, 2015 Neil Avenue, Columbus, OH 43210 USA; [3]Istituto Nazionale di Fisica della Materia, Laboratorio Tecnologie Avanzate Superfici e Catalisi, Area di Ricerca, Trieste, I 34012 Italy

Low energy cathodoluminescence spectroscopy (CLS) reveals that thin (2 nm) controlled interface layers (CILs) substantially improve the resistance of ZnSe/GaAs heterojunctions to thermally-induced defect formation. Previously, Franciosi and coworkers [1] showed that changes in ZnSe growth stoichiometry on GaAs could be used to alter the interface dipole and achieve heterojunction band offset (HJBO) changes of ~ 0.6 eV. Such nonstoichiometric epilayer growth also alters the formation of deep levels, however, and a particular drawback for Se-rich epilayers is a major increase in diffusion-induced defect formation at elevated temperatures [2]. Franciosi et al. have then used off-stoichiometric CIL layers to achieve comparable HJBO changes [3], and their effect on defect formation has now been measured. - Molecular beam epitaxy specimens consisted of a lightly n-doped ($1 \infty 10^{17}$ cm^{-3}) GaAs buffer layer 500 nm thick and an epilayer of nominally undoped ZnSe 150 nm thick, separated by a 2-nm-thick CIL of ZnSe. This intermediate layer was grown Se-rich using a Zn-to-Se beam pressure ratio (BPR) of ~ 0.1. We used relatively low electron beam energies ranging from 0.5 keV to 4.5 keV to obtain depth-dependent CLS spectra extending tens to hundreds of nm below the free surface. With increasing beam energy, the CLS excites free electron-hole pairs selectively in the near surface region, the ZnSe interior, the ZnSe/GaAs interface or the bulk. In addition to the near-band-edge emissions from GaAs and ZnSe, our room temperature spectra exhibit a peak feature centered at ~ 0.87 eV at all ZnSe excitation depths and 1.2 eV emission from a state localized near the free ZnSe surface for low (500 eV) excitation energies. After annealing to 425 °C, we observe the onset of a defect peak at 1.85 eV which dominates the entire spectrum. This peak is commonly assigned to Ga-Zn antisite defects, possibly including a Zn vacancy. For ZnSe epilayers grown under Se-rich (BPR = 0.1) conditions throughout, Raisanen et al. [2] reported the onset of this feature at much lower temperatures, i.e. below 325 °C. This dramatic threshold increase indicates that the stoichiometry of the ZnSe film, vs. that of the interface, promotes the interdiffusion leading to defect formation. Hence, our results suggest that HJBO engineering and defect formation can be controlled independently. - In conclusion, this work demonstrates both the utility of CLS for probing thin layers and buried interfaces under different growth conditions, as well as the effectiveness of interfacial layers only a few monolayers thick in altering interfacial bonding without degrading the heterojunction's resistance to thermally-induced - (1) R. Nicolini, L. Vanzetti, G. Mula, G. Bratina, L. Sorba, A. Franciosi, M. Peressi, S. Baroni, R. Resta, A Baldereschi, J. E. Angelo, W. W. Gerberich, Phys. Rev. Lett. 72, 294 (1994). - (2) A. D. Raisanen, L. J. Brillson, L. Vanzetti, A. Bonanni, A. Franciosi, Appl. Phys. Lett. 66, 3301 (1995). - (3) A. Bonnani, L. Vanzetti, L. Sorba, A. Franciosi, M. Lomascolo, P. Prete, R. Cingolani, Appl. Phys. Lett. 66, 1092 (1995).

9:20 AM, R4

Correlation Between Deep Traps and Kink Effect in AlInAs/InP HFETs: ABDELKADER SOUIFI[1]; Bogdan Georgescu[1]; Marcel Py[2]; Georg Post[3]; Gérard Guillot[1]; [1]INSA de Lyon, Laboratoire Physique de la Matiere, Bat. 502, 20, Av. Albert Einstein, Villeurbanne, Rhone 69621 France; [2]EPFL, Institut de Micro-Optoelectronique, Ecole Polytechnique Federale, Lausanne CH-1015 Switzerland; [3]France Telecom, CNET-PAB, 196, Av. H. Ravera, Bagneux, Paris 92225 France

This work reports on a detailed investigation of deep traps in AlInAs/InGaAs/InP composite channel HFETs which are promising devices for optical telecommunications. For this study, we have used three different techniques in order to determine the activation energies and the capture cross section of the deep levels. All the measurements have been done in the 80 - 500 K temperature range, and a special interest has been focussed on the deep traps observed at room temperature. The first technique is the current transient spectroscopy (CTS) which consists of analyzing the drain current transients after applying a short variation in the Vgs polarization. In a second step, we have studied the frequency dispersion of the output conductance of the transistors. In that case, the Vgs bias is kept constant, a modulation is applied on the drain-source bias, and the gain and phase signals between Vds and Ids are analyzed in the 100Hz-100KHz frequency range. Finally, low frequency noise measurements have been studied in the same frequency range for the drain and gate currents. The principal observation from these three measurement techniques, is that a predominant electron trap is detected around 300K. All the techniques give a comparable value for the activation energy which is around 0.5 eV. This level is connected to an electron trap previously detected in AlInAs materials grown in the same MOCVD chamber. From our experimental conditions, we have also deduced that the electron trap observed in the transistors originates from the AlInAs layers, and specially the barrier layers. Our interest is to connect this deep level to the observation of a kink effect easily evidenced in the output characteristics of our HFETs. A first indication which shows that both phenomenon could be connected is the similar frequency and temperature behaviors. In order to go further in our hypothesis, we have studied the optical properties of the electron trap, and we have compare the results with the Id-Vd characteristics variations under the same optical spectral excitation. These measurements have been recorded at low temperatures, where the kink phenomenon is quite important, and where it was possible to obtain a photoionization of the deep traps. Our measurements have shown that it is possible to suppress the kink effect by an optical excitation, and that it is possible to obtain a photoionization of the electron trap. The interesting point is that both results on bulk AlInAs and HFETs are obtained exactly for the same threshold energy. Once again, this fits well with our first hypothesis. Finally, our electro-optical study shows a direct correlation between deep electron traps in the AlInAs barrier layers and the kink effect in these devices.

9:40 AM, R5+

Effect of Surface Passivation on Vacancy Indiffusion and Reliability of Pseudomorphic InGaAs-InAlAs-InP HEMT Material: DWIGHT C. STREIT[1]; Benjamin N. Wang[1]; [1]TRW, One Space Park D1-1302, Redondo Beach, CA 90278 USA

We have studied the effect of silicon nitride surface passivation on the stability of pseudomorphic InGaAs-InAlAs-InP HEMT material grown by molecular beam epitaxy. We find that without surface passivation these epitaxial HEMT structures are degraded during thermal annealing in a nitrogen ambient at temperatures above 450°C by layer intermixing and quantum well destruction. However, silicon nitride surface passivation protects against surface vacancy indiffusion and preserves the inherent stability of the pseudomorphic InGaAs-InAlAs quantum well system up to annealing temperatures of 780°C. These results have important implications for the fabrication of HEMT devices and circuits, and for the thermal annealing schedules currently used during InGaAs-InAlAs-InP HEMT processing. The epitaxial layer structure for the passivated

and nonpassivated HEMT samples were identical. They consisted of an InAlAs buffer layer grown lattice matched to InP substrates by solid source MBE, a pseudomorphic InGaAs channel with 60% InAs, an InAlAs donor layer with silicon planar doping, and an InGaAs surface layer. Hall measurements on the original unannealed samples gave sheet concentrations of Ns = $3.3x10^{12}$ cm^{-2} and room temperature mobility of about 11,000 cm^2/Vs. The samples were annealed side-by-side at the same time at temperatures ranging from 300°C to 780°C. A fresh sample cleaved from the original 3-inch wafer was used for each anneal. Room temperature Hall-effect measurements were made on each 1 cm x 1 cm sample before annealing to ensure uniformity of starting material. The unpassivated HEMT samples showed degredation in electrical characteristics at temperatures above 450°C. Sheet concentration and electron mobility decreased rapidly as the temperature was increased incrementally above 450°C. Unpassivated samples annealed at 600°C had sheet concentration reduced to Ns = $0.5x10^{12}$ cm^{-2}, and room temperature electron mobility reduced to about μ = 100 cm^2/ Vs. Photoluminescence response measured at 4.2K was likewise reduced to a small fraction of the original intensity. Auger depth profiling revealed that the InGaAs channel used for electron transport was intermixed with the InAlAs cladding layers, a classic quantum well destruction phenomenon due to surface vacancy indiffusion. The silicon nitride passivated HEMT samples were robust to annealing temperatures of 780°C. Hall measurements revealed virtually no change in sheet charge concentration or electron mobility, 4.2K photoluminesence from the InGaAs quantum well revealed no degradation in luminescence intensity, and Auger depth profiling revealed no layer intermixing for the passivated HEMT samples up to the maximum 780°C annealing temperature used for this experiment. These results indicate that surface passivation protects against vacancy indifussion and layer intermixing. They also indicate that extreme caution must be used during the processing of these high performance HEMT wafers to ensure protection of the device material during any thermal anneal process steps.

Thursday AM, June 25, 1998

Session S. Defects in Nitrides

Room: 120
Location: Olsson Hall

Session Chair: Z. Lilienthal, Lawrence National Laboratory, Materials Science Division, Berkeley, CA 99720 USA

10:20 AM, S1

The Relationship Between Microstructure and Carrier Transport In GaN Grown on A-Plane Sapphire: MARK E. TWIGG[1]; R. L. Henry[1]; A. E. WICKENDEN[1]; D. D. KOLESKE[1]; J. C. CULBERTSON[1]; [1]Naval Research Laboratory, Code 6812, 4555 Overlook Avenue, S.W., Washington, DC 20375-5320 USA

The objective of this study is to elucidate the effects of microstructure on carrier transport in GaN films grown on a-plane sapphire via metal-organic vapor phase epitaxy. We have addressed these concerns by studying Si-doped GaN films in which the mobility and carrier concentration are two to three times larger at the wafer edge than at the wafer center. Despite large differences in carrier mobility, cross-sectional transmission electron microscopy (XTEM) observations indicate that the dislocation density at the center of the sample is not measurably different from the dislocation density at the edge of the sample. Throughout the wafer the dislocation density was found to be on the order of 1e8/cm2. It is apparent from XTEM, however, that the GaN grain size at the wafer edge is approximately 1 micron, whereas the GaN grain size in the wafer center ranges from 0.5-0.1 micron. Smaller grain size leads to a lower carrier mobility in the wafer center, because recombination is enhanced by the presence of grain boundaries. From XTEM observations of the AlN nucleation layers (NL), we have determined that the difference in grain size, in the subsequent GaN growth from center-to-edge, can be traced to differences in the annealed NL from center-to-edge. Throughout the wafer, the as-grown NL was seen to form with a variety of orientations, consisting of both zinc blende and wurtzite AlN, with wurtzite grains oriented with the c-axis perpendicular to the plane of the substrate as well as in other directions. Upon annealing, however, many grains of the NL at the wafer edge assumed a well-defined orientation that is consistent with proper growth: with the AlN [1-100] direction aligned with the sapphire [1-100] direction and the sapphire c-axis [0001] aligned with AlN [11-20]. There is no direct evidence, however, of this proper growth configuration in the NL at the wafer center. The effect of annealing on the structure of the NL from center-to-edge suggests the critical role of NL annealing on the quality of subsequent GaN growth.

10:40 AM, S2

Theoretical Investigation of Edge Dislocations in GaN: ALAN F. WRIGHT[1]; [1]Sandia National Laboratories, MS 1415, PO Box 5800, Albuquerque, NM 87185-1415 USA

GaN films grown on sapphire substrates have dislocation densities as high as 2 x 10^{10} cm^{-2}, orders of magnitude greater than are found in device-quality films of other III-V compounds. The successful fabrication of optical and electronic devices from such highly defected films is therefore surprising and has prompted the suggestion that dislocations in GaN do not produce defect levels lying in the forbidden gap. To investigate this possibility, we have determined the relaxed structures and formation energies for an edge dislocation in GaN using first-principles theoretical techniques. Filled and open core structures are examined as well as structures having vacancies along the dislocation core. Formation energies for these structures are calculated both as a function of the growth conditions (Ga-rich or N-rich) and the Fermi level. From the formation-energy dependence of the on Fermi level, the positions of defect electronic levels in the gap can be deduced. Comparisons will be made between these defect levels and those produced by bulk point defects. This work was supported by the United States Department of Energy under Contract No. DE-AC04-94AL85000.

11:00 AM, S3+

Photoelectrochemical Etching of GaN for Materials Characterization: C. YOUTSEY[1]; L. T. Romano[2]; I. Adesida[1]; [1]University of Illinois, Department of Electrical and Computer Engineering and Microelectronics Laboratory, Urbana, IL 61801 USA; [2]Xerox Palo Alto Research Center, Palo Alto, CA 94306 USA

The most effective wet etching of GaN films has been obtained through photoenhanced wet etching techniques. The photo-etched GaN surface morphologies are generally quite rough, a result which has been attributed to the high defect density of the nitride films. Historically, wet etching methods have been widely used for revealing crystal imperfections in semiconductors and metals such as dislocations. The characterization of defects in epitaxial GaN films on sapphire and SiC is currently an area of intense research. The success of future nitride-based electronic and optoelectronic devices will depend upon the identification and minimization of extended structural defects. Most recently, epitaxial lateral over-growth (ELOG) techniques have played a key role in the growth of GaN-based laser structures with demonstrated lifetimes in the thousands of hours. These long lifetimes are a direct consequence of reduced defect densities in the active region of the device. In this work, we will discuss our latest results on the photoelectrochemical (PEC) etching of n-type GaN films and the correlation of etched surface morphologies with the defect structure of the nitride films. In addition to demonstrating the utility of the PEC process as for materials characterization, we will discuss techniques for improving the etched surface morphology. The etching is carried out using a Hg arc lamp for illumination and aqueous KOH solution. The etched films are characterized by scanning and transmission electron microscopy, atomic force microscopy, and cathodoluminescence.

11:20 AM, S4

Characterization of Defect Levels in N-Type $Al_{0.15}Ga_{0.85}N$/GaN Heterostructures: XIAOZHONGI DANG[1]; Edward T. Yu[1]; Karim S. Boutros[2]; Joan M. Redwing[2]; [1]University of California, San Diego, Department of Electrical and Computer Engineering, 9500 Gilman Drive, La Jolla, CA 92093-0407 USA; [2]Epitronics/ATMI, 21002 North 19th Avenue, Suite 5, Phoenix, AZ 85027-2726 USA

Despite remarkable advances in nitride optoelectronic and electronic device performance, it is well recognized that numerous and varied structural and electronic defects exist in nitride materials; an understanding of these defects and their potential influence on device properties is of increasing importance for

optimization of device performance. We have performed detailed investigations of defect levels in n-type $Al_{0.15}Ga_{0.85}N$/GaN heterostructures using persistent photoconductivity (PPC) measurements and deep level transient spectroscopy (DLTS). Samples were grown by MOCVD, and consisted of 3 micron nominally undoped GaN grown on a sapphire substrate, followed by a nominally undoped $Al_{0.15}Ga_{0.85}N$ layer either 30 nm or 50 nm in thickness. These structures are very similar to those typically used in nitride heterojunction field-effect transistors (HFET's). Bulk (about 1 micron) layers of GaN and $Al_{0.15}Ga_{0.85}N$ grown under similar conditions were found to have resistivities of approximately $1x10^5$ Ohm-cm or higher. Schottky diodes were fabricated by deposition of Ti/Al to form Ohmic contacts, followed by deposition of Ni/Au to form Schottky contacts. Despite the low dopant concentrations in the epitaxial layers, capacitance-voltage profiling revealed the formation of a two-dimensional electron gas (2DEG) at the $Al_{0.15}Ga_{0.85}N$/GaN interface, which previous studies have shown is largely a consequence of the piezoelectric effect.[1] Photocurrent was measured by applying a constant bias to the illuminated diode. Persistent photoconductivity effects are clearly observed in these samples. The decay in photocurrent after turning off the illumination is well described by a stretched-exponential function with a typical time constant of about $1x10^4$ s. Photocurrent spectra were measured for excitation energies ranging from 2.0 eV to 4.0 eV and below 1.5eV to investigate the energy distribution of trap levels. A broad distribution of defect levels is observed with excitation energies extending from band-edge to about 2.5eV. No levels were observed in the measurements with excitation energy lower than 1.5eV. Measurements performed using a variety of illumination geometries allowed us to distinguish between spectral features arising from the GaN layer and those originating in $Al_{0.15}Ga_{0.85}N$ and/or $Al_{0.15}Ga_{0.85}N$/GaN interface. Effects of annealing on photocurrent spectra were also investigated. DLTS was also used to characterize these samples. For the reverse-bias voltages used in these studies, the presence of the 2DEG at the $Al_{0.15}Ga_{0.85}N$/GaN interface limits the depletion region in the Schottky diode to the $Al_{0.15}Ga_{0.85}N$ layer. Thus, only the deep levels in $Al_{0.15}Ga_{0.85}N$ are detected. At least two deep levels with activation energies in the range of 0.5 to 1.0 eV have been detected. How ever, shifts in the positions of the DLTS peaks with fill pulse width were observed, suggesting that deep levels are present over an extended range of activation energies. These measurements have also been compared with DLTS studies performed of 1 micron strain-relaxed $Al_{0.15}Ga_{0.85}N$ layers grown by MOCVD. [1] E. T. Yu, G. J. Sullivan, P. M. Asbeck, C. D. Wang, D. Qiao, and S. S. Lau, Appl. Phys. Lett. 71, 2794 (1997). · Support for this work was provided by BMDO (Dr. Kepi Wu) monitored by USASMDC.

11:40 AM, S5

Magnetic Resonance Studies of InGaN-Based Quantum Well Diodes: W. E. CARLOS[1]; E. R. Glaser[1]; T. A. Kennedy[1]; Shuji Nakamura[2]; [1]Naval Research Laboratory, Code 6862, 4555 Overlook Ave. SW, Washington , DC 20375 USA; [2]Nichia Chemical Industries, Inc., 491 Oka, Kaminaka, Anan, Tokushima , 774 Japan

Quantum well structures are a integral part of laser diodes, light-emitting diodes and other GaN-based opto-electronic devices. In this work we have performed electrically and optically detected magnetic resonance (EDMR and ODMR) studies of $In_xGa_{1-x}N$ single quantum well diodes to understand the defects and recombination processes in these structures. These techniques offer greatly enhanced sensitivity over conventional EPR, as well as access to centers not in thermal equilibrium and coupling to electrical and optical processes in a device structure. For most biases, EDMR is dominated by a single broad isotropic resonance at g=2, while in the (PL-based) ODMR two resonances are observed on the emission from the quantum well: an electron resonance with $g_{||}$=1.934, g_{perp}=1.928 and a hole resonance with $g_{||}$=2.077, g_{perp}=1.996 for x=0.4. The electron resonance is consistent with expectations for the g value in $In_xGa_{1-x}N$ (x=0.4) and the hole resonance is very similar to observations in Mg-doped GaN. The differences in the two experiments may be due to the electric fields in the devices (both due to the p-i-n structure and piezoelectric effects) which separate the electrons and holes in the ODMR. This gives the relatively long radiative lifetimes (as long as ~0.2 msec) measured in the ODMR which facilitate the observation of the resonance. In the EDMR experiments the electric fields are reduced and the signal is primarily due to a reduction in the nonradiative recombination at resonance. The intensities of the spectra in either technique decrease rapidly with increasing carrier density. While the ODMR is always emission-enhancing, the sign of the EDMR changes from a current-quenching signal at low biases to a current-enhancing signal at high biases. A comparison of the two techniques as a function of bias and excitation power (i.e., electric field) will be discussed in detail.

THURSDAY PM

June 25, 1998

Session T. Novel and Artificially-Structured Thermoelectric Materials

Room: 005
Location: Olsson Hall

Session Chairs: Tim Sands, University of California, MSME Department, Berkeley, CA 94720-1760 USA; Gang Chen, UCLA, Los Angeles, CA 90095

1:30 PM, T1

The Nanofabrication of Quantum Wires for the Next Generation of Thermoelectrics: DAVID DEMSKE[1]; Jack Price[1]; Noel Guardala[1]; Norris Lindsey[1]; Karen Witkoski[1]; Bob Brizzolara[1]; Jagadish Sharma[1]; Lourdes Salamanca-Riba[2]; Chris Kang[2]; [1]Naval Surface Warfare Center, Carderock, 9500 Macarthur Blvd., West Bethesda, MD 20817-5700 USA; [2]University of Maryland, Dept. of Nuclear Engineering, College Park, MD USA

Recently, there has been considerable interest in low-dimensional, quantum-confined structures for improved thermoelectric materials. The traditional thermoelectric or Peltier cooler is a small solid-state refrigerator which converts direct electrical current into a cooling effect by means of electron transport energy jumps at the junction between two dissimilar semiconductors exhibiting high Seebeck coefficients. Since it has no moving parts, contains no CFC fluids and its performance is size-independent, its operational reliability shows compelling promise as a compact, quiet, cooling device and should be especially beneficial where miniaturization and environmental compliance constraints are an issue. In this context, solid-state thermoelectric coolers are particularly attractive in a wide variety of cooling applications from infrared optical sensor cooling to microchip diode laser cooling for diode laser-fiber optic interconnects and various communication linkages. This paper describes an ongoing experimental research effort to fabricate and characterize a particular class of semiconductor-insulator experimental research effort to fabricate and characterize a particular class of semiconductor-insulator nanocomposite materials (Quantum-Well Wire Heterostructures) for the purpose of enhancing the figure of merit in specific thermoelectric (TE) materials. Until very recently, the synthesis of 1D thermoelectric nanocomposites had been virtually nonexistent or rudimentary at best. The results of this research are expected to dramatically improve the next generation of high performance, all-solid state TE devices. Under proper quantum size-confinement and heterostructural conditions, bismuth (Bi), a semimetal, theoretically has a potential for significantly improving the dimensionless material figure of merit (ZT). Our proof-of-principle efforts to date have primarily concentrated on verifiably electrodepositing Bi wires into a high density array of nanochannels embedded in templates made of mica, an extremely low thermally conductive insulator possessing a high heterojunction potential off-set. This research thrust uses a novel but practical means to fabricate these wire arrays by employing a two-part synthesis procedure. Using our heavy-ion accelerator to generate nanosize channels (nuclear damage track imprints) in 33 micron thick mica, Atomic Force Microscope (AFM) micrographs verify that we have succeeded in fabricating templates containing arrays of columned nanochannels having diameters down to 13 nanometers, thus providing nanochannels with a length-to-diameter aspect ratio of 1000:1 and channel densities up to $10^{15}cm^{-2}$. To fabricate these templates, we have irradiated the mica with a dense collimated beam of 6 MeV carbon ions at a 1.5×10^{15} ions/cm^2 dose level. Scanning electron micrographs show that these nuclear damage track registrations have smooth, non-tapered walls of uniform cross section. In addition, we have developed a solution-electrodeposition process where we are presently fabricating uninterruptedly connected, 33 micron long Bi wires having submicron diameters. Having established the proper electroplating electrolyte composition and electrolysis conditions for Bi, we are employing a PC processor-driven potentostatic/galvanostatic system for electrochemically in-

corporating Bi as the injectant into nanochannel templates. This synthesis procedure provides the means for our near future efforts in verifiably synthesizing Bi wires at the nanoscale size level. Our immediate goal is to use this recently established solution-electrodeposition process to reliably produce dense ultrathin Bi wire ensembles in a variety of template materials with 8.0 to 10.0 nanometer diameter channels, a regime where significant quantum-enhanced ZT effects can be expected to result.

1:50 PM, T2

Preparation and Characterization of New and Novel Pb Chalcogenide-Based MBE-Grown Superlattice Structures with Enhanced Thermoelectric Figures of Merit: THEODORE C. HARMAN[1]; David L. Spears[1]; Michael W. Walsh[1]; [1]MIT Lincoln Laboratory, Elect-Optical Materials & Devices, 244 Wood Street, Lexington, MA 02173-9108 USA

High-quality $Pb_{1-x}Eu_xTe$/PbTe multiple-quantum-well (MQW) and superlattice structures have been grown by molecular beam epitaxy and yield high two-dimensional thermoelectric power factors P_{f2D} and figures of merit $Z_{2D}T$. The measured 300 K thermoelectric properties have been compared with that of the best bulk PbTe. P_{f2D} values up to 130 and over 150 $\mu Wcm^{-1}K^{-2}$ have been measured at 300 K for n-type1 and p-type2 MQW samples, respectively. Values of Z2DT >1.2 have been achieved for these n-type PbTe quantum wells and Z2DT >1.5 has been attained for the p-type quantum wells at 300 K. At 400 K, Z2DT = 2.3 has been achieved. However, the overall or three-dimensional (3D) thermoelectric figures of merit of the Pb1-xEuxTe/PbTe superlattice and MQW structures were not as good as bulk PbTe. Subsequently, we have found other Pb chalcogenide-based thermoelectric superlattice structures with significantly enhanced 3D thermoelectric power factors and figures of merit. We will discuss the growth of these new and novel structures as well as characterization results, which include x-ray diffraction spectra and Hall coefficient, electrical resistivity and Seebeck coefficient data vs temperature from 80 to 580 K. *This work was sponsored by the Defense Advanced Research Projects Agency (DARPA), Department of the Navy, and the Army Research Office under AF Contract No. F19628-95-0002. The opinions, interpretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force. References:1. T. C. Harman, D. L. Spears, and M. J. Manfra, J. Electron. Mater. 25, 1121 (1996). 2. T. C. Harman, D. L. Spears, D. R. Calawa, S. H. Groves, and M. P.Walsh, Proc. XVI Int. Conf. on Thermoelectrics, Dresden (Germany), (1997).

2:10 PM, T3

Thermoelectric Transport in PbTe Superlattices: THOMAS L. REINECKE[1]; David A. Broido[2]; [1]Naval Research Laboratory, Code 6877, 4555 Overlook Ave, S.W. , Washington, DC 20375 USA; [2]Boston College, Department of Physics, Higgins 355, Chestnut Hill, MA 02167 USA

The possibility that superlattice systems may provide high thermoelectric figures of merit ZT has been of great interest in recent years [1]. It was suggested [2] that ZT in these systems might be greatly enhanced in the fully confined limit in which the potential barriers were taken to be infinite and the effects of the barrier layers were neglected. A quantitative description of thermoelectric transport in realistic superlattices is needed in order to make reliable assessments of these materials for potential applications. In earlier work [3] we studied the effects of heat transport along the barriers and of carrier tunneling through the barriers on thermoelectric transport in superlattices. In recent work we have developed a complete, quantitative theory of the electronic contribution to thermoelectric transport in superlattices in which we take into account also the well width dependence of the carrier scattering rates and of the lifting of the degeneracy in multiband systems. We have used this approach to examine whether ZT is enhanced in the fully confined limit [3]. In the work presented here we examine the thermoelectric transport properties and figure of merit ZT in realistic PbTe superlattices with finite potential barriers. We find that the well width dependence of the carrier scattering rates and the lifting of the valley degeneracy have important effects on these properties and that these effects depend on the barrier height V. For example, we have calculated the carrier mobility due to electron-phonon scattering as a function of well width for PbTe superlattices with for V= 200 meV and barrier width of 200A. We find that in this case the spatial extent of the laterally confined carrier wavefunctions decreases only weakly with decreasing well width. This is a result of barrier penetration, and it results in a relatively weak dependence of the mobility on well width, which is in general accord with recent experimental data [5]. We have calculated ZT as a function of well width for PbTe superlattices with barrier widths of 200A and with barrier heights V=200 meV, 400 meV and with infinite barrier height. These results show that for a given well width ZT increases with decreasing barrier height due to the increased contribution of the oblique valleys in PbTe with finite V. Thus we see in the case of multivalley materials of interest that the highest ZT will occur for relatively low potential barriers. The lattice thermal conductivity plays a key role in determining ZT, and recent experimental data suggests that it is considerably reduced in superlattices systems. We have calculated the effects of interface scattering on the lattice thermal conductivity using a Boltzmann equation approach and find that for decreasing well width it decreases continuously as compared to bulk. We have used these results for the lattice thermal conductivity in our detailed theoretical approach for the electronic properties, we find that resulting ZT in PbTe superlattices increases substantially for decreasing well widths. This work was supported in part by the US Office of Naval Research. [1] G. Mahan, B. Sales and J. Sharp, Physics Today 50, 42 (1997). [2] L. D. Hicks and M. S. Dresselhaus, Phys. Rev. B 47, 12727 (1993). [3] D. A. Broido and T. L. Reinecke, Phys. Rev. B 51, 13797 (1995). [4] D. A. Broido and T. L. Reinecke, Appl. Phys. Lett. 70, 2834 (1997). [5] T. C. Harman, private communication.

2:30 PM, T4

Factorial Enhancement in Thermoelectric Figure of Merit with Si/Ge Superlattice Structures: R. VENKATASBRAMIAN[1]; E. Siivola[1]; T. Colpitts[1]; [1]Research Triangle Institute, Research Triangle Park, NC 27709 USA

Freestanding, thin-film, Si/Ge superlattice (SL) structures over a wide range of periods, from ~300A to 10A, have been experimentally investigated for their thermoelectric properties in the plane of the SL interfaces. We have observed a several-fold enhancement in the power factor at 300K in these Si/Ge SL structures, compared to thin-film SiGe and bulk SiGe alloys. The thermoelectric power factor and Hall-effect measurements, with model calculations for effective conduction-band density of states, have been used to understand the mechanism behind the strong enhancement in power factor in these apparently weakly-quantum confined SL structures. AC calorimetry measurements have also been completed to determine the in-plane thermal diffusivity of these Si/Ge SL thin-films. The variation of thermal conductivity (k) with the SL period appears complex, with reduction in k coming apparently from both short-period and lattice-rnismatch effects. Finally, we will present the first experimental construction of a factorial improvement in the three-dimensional figure-of-merit (ZT_{3D}) of Si/GeSL structures with respect to comparable bulk SiGe alloys, with all the properties measured in the same direction, suggesting a proof-of-concept validation for thin-film SL structures. The implications of the ZT enhancement with Si/Ge SL structures would be significant for a variety of applications.

2:50 PM, T5

Structural and Thermoelectric Properties of MBE-Grown Bi_2Te_3 Thin Films: S. CHO[1]; A. DiVenere[1]; Y. Kim[1]; G. K. Wong[1]; J. B. Ketterson[1]; J. R. Meyer[2]; C. A. Hoffman[2]; [1]Northwestern University, Department of Physics and Astronomy & Material Research Center, 2145 Sheidan Road, Evanston, IL 60208-3112 USA; [2]Naval Research Laboratory, Code 5613, Washington, D.C. USA

High efficiency thin film thermoelectric devices are widely foreseen achieving numerous applications in the microelectronics industry such as to dissipate the generated heat of devices on the circuit of board. Bi_2Te_3 and its solid solutions are well known good thermoelectric materials for near-room temperature thermoelectric applications. A number of techniques have been used in the fabrication of Bi_2Te_3 thin films such as magnetron sputtering, laser ablation, MOCVD and molecular beam epitaxy (MBE) on various substrates. Little work has been reported on the growth of high quality Bi_2Te_3 thin films. Since one prerequisite for high performance of the device is high mobility, this effort is directed toward achieving this goal. In this paper, we describe the growth, structural and transport properties of MBE-grown Bi_2Te_3 thin films. We used CdTe(111)B substrate to grow Bi_2Te_3 thin films and the lattice mismatch was 4.4 %. The films were characterized by in-situ reflection high-energy electron diffraction (RHEED), TEM and X-ray diffraction pattern. They show that Bi_2Te_3 films on CdTe(111) grows along the (00.l) in the hexagonal cell with layer-by-layer growth mode, resulting in a smooth surface, and a X-ray Bragg peak FWHM of 0.2 Å, attesting to the high crystallinity of the films. Seebeck coefficient and electrical conductivity of the undoped Bi_2Te_3 films were ~200 uV/K and 10^3 1/ Ωcm, respectively, comparable to the single crystal bulk value. We could observe the degenerate and nondegenerate behavior in the transport measurements by controlling the doping level. The temperature dependencies of the Seebeck coefficient, Hall

mobility and electrical conductivity for the doped and undoped samples will be discussed.

3:10 PM Break

3:30 PM, T6

Optimizing the Thermoelectric Properties of Filled Skutterudites: DONALD T. MORELLI[1]; Gregory P. Meisner[1]; Jihui Yang[1]; Siqing Hu[2]; Ctirad Uher[2]; [1]GM Global R&D Operations, Physics and Physical Chemistry Department, Mail Code 480-106-224, 30500 Mound Road, Warren, MI 48090 USA; [2]University of Michigan, Department of Physics, Randall Laboratory, Ann Arbor, MI 48090 USA

Rare-earth filled skutterudites possess enhanced thermoelectric figure of merit and are candidate materials for next generation thermoelectric power generation systems. The figure of merit is given by $Z = S^2\sigma / K$, where S is the Seebeck coefficient, σ the electrical conductivity, and K the thermal conductivity. Traditionally the best thermoelectric materials are heavily doped semiconductors with high carrier mobility υ (providing for large σ) and low lattice thermal conductivity K_L. The lattice thermal conductivity decreases with increasing average atom mass (M) and increasing number of atoms per unit cell (n). Thus, for instance, the binary semiconductor PbTe ($\upsilon \cong 1750$ cm^2 /V.s, M = 167.5, n = 8, $K_L \cong 10^{-2}$ W/cm.K) has desirable thermoelectric properties. The unfilled skutterudite $CoSb_3$ is a covalently bonded semiconductor with n = 16, M = 108, and a hole mobility $\upsilon \cong 3000$ cm^2 /V.s. Unfortunately, the lattice thermal conductivity is only moderately low ($K_L \cong 10^{-1}$ W/cm.K). The structure of this compound, however, features two large voids in the unit cell which can be filled with rare earth atoms to a level of approximately 10%. It has been well established by X-ray thermal parameter analysis that these rare earth atoms exhibit a "rattling" motion inside of the Sb cage which surrounds them. This rattling induces significant phonon scattering and results in an order of magnitude reduction in thermal conductivity of filled skutterudites relative to their unfilled counterparts, a key ingredient for producing large Z. Further, by alloying with Fe on the Co site, the rare earth filling fraction can be increased to near 100%. All of the relevant fundamental thermoelectric transport parameters depend sensitively on both the Fe/Co alloying and rare earth filling fraction. We show that the structural and thermal transport properties of these fractionally filled skutterudites can be rationalized if these compounds are considered as simple solid solutions of fully filled and unfilled constituents. This description provides a route for optimizing the transport properties to produce maximum figure of merit.

3:50 PM, T7

AB_2X_4 Compounds and Other New Thermoelectric Materials Studied At JPL: JEFF SNYDER[1]; Thierry Caillat[1]; Jean-Pierre Fleurial[1]; Alexander Borshchevsky[1]; [1]Jet Propulsion Lab, 277-207 JPL/Caltech, Pasadena, CA 91109-8099 USA

An overview of the thermoelectric materials research program at JPL will be given. I will provide an update on the progress in Skutterudite, Zn_4Sb_3, and Chevrel based materials. Special emphasis will be given to new classes of materials being studied at JPL, namely AB_2X_4 chalcogenides. Two major structure types exist in this stoiciometry, Spinel and defect NiAs. Both structures show low lattice thermal conductivity over a broad temperature range. Many of the NiAs type compounds behave like metals; $FeCr_2Se_4$ however, is a semiconductor. Of the many chalcogenide spinels, $CuCr_2Se_4$ is a metal with a relatively high mobility and can be doped such that it becomes a semiconductor. The electronic properties and the potential of these compounds as thermoelectric materials will be discussed.

4:10 PM, T8

Non-Isothermal Thermionic Emission in InGaAsP Heterostructures: ALI SHAKOURI[1]; Patrick Abraham[1]; John E Bowers[1]; [1]University of California Santa Barbara, Electrical and Computer Engineering, Engineering I, Santa Barbara, CA 93106 USA

Thermoelectric coolers are used with many high power optoelectronic devices because of the need to stabilize the characteristics such as operating wavelength or the threshold current. Coolers based on InGaAsP material can be monolithically integrated with long wavelength optoelectronic components. The use of thermionic emission in heterostructures will permit to enhance cooling capacities beyond linear transport regime. Selective emission of hot carriers over a barrier layer from cathode to anode will cool down the emitter junction. With appropriate band discontinuities one can optimize the cooling power or the efficiency. An important parameter to minimize is amount of heat generation in the barrier. Monte Carlo simulations of the electron transport i n III-V thin barrier heterostructures are used to calculate the bias dependence of the electron energy relaxation length. It is shown that this energy relaxation length has a maximum as a function of electric field that describes the interplay between polar optical phonon emission and intervalley scattering. Implications for the design of heterostructure integrated thermionic (HIT) coolers are discussed. A Single barrier HIT structure consisting of 0.3 μm InGaAs emitter, 1 μm InGaAsP (lambda=1.3 μm) barrier and 0.5 μm InGaAs collector, all lattice matched to InP substrate, is grown using MOCDV. Nonisothermal thermionic emission is studied experimentally with an integrated diode temperature sensor on the emitter side. Cooling by a few degrees centigrade over one micron thick barrier is reported.

4:30 PM, T9

Optimized Doping Profiles for Thermoelectircl Cooling Devices Based on BI2TE3-SB2TE3 Alloys: J. R. MADDUX[1]; W. A. Jesser[1]; [1]University of Virginia, Dept. of Materials Science and Engineering, Charlottesville, VA 22903 USA

Recent interest in high performance thermoelectric (TE) energy conversion has led to several proposals for increasing the conversion efficiency of TE materials and devices. One such proposal has involved the controlled spatial variation of TE properties along the length of the thermoelements in a TE cooling device. This spatial variation of properties is engineered such that the heat flow in the device is optimized for a given cooling application, thereby improving cooling performance. The extent of the improvement one may obtain through this technique is found to be highly dependent on the particular application for which the device is intended, as well as the operating temperature range of the device. The conventional TE figure-of-merit, Z, has been used to adequately model the steady-state cooling performance of devices with spatially uniform properties. However, the behavior of nonuniform devices is more complex, and cannot be adequately described with a single parameter such as Z. Additionally, the effects of temperature dependent TE properties are more pronounced in nonuniform devices, and must be accounted for if one is to obtain an accurate analysis of device performance. In the present study, a framework is developed for analyzing and optimizing the various measures of performance in nonuniformly doped TE cooling devices. Three measures of performance are examined: (1) maximum temperature difference, (2) maximum heat pumping capacity, and (3) coefficient of performance. This analysis is performed using a 1-D TE device model, coupled with temperature and doping dependent models for the TE properties of the thermoelements. This methodology is applied to simulate the cooling performance of TE devices composed of Bi_2Te_3- and Sb_2Te_3-based solid solution alloys. A comparison of simulated and experimental results shows good agreement between the two, and serves to verify the accuracy of the simulation models. A nonlinear optimization routine is used with the device simulation procedure to determine optimal doping profiles for a given measure of cooling performance, (1)-(3) above. Optimized doping profiles for the Bi_2Te_3- and Sb_2Te_3-based alloys are calculated for each of these parameters individually. Results of this procedure demonstrate that different doping profiles are needed to optimize the device for a given application. The measures of performance, (1)-(3) above, are not simultaneously maximized by the same doping profile. The extent of the improvement also varies widely, depending on the parameter of interest, and is found to be highly dependent on the operating temperature range of the device. Graphical data will be provided which summarizes all of these results.

4:50 PM, T10

Late News

Thursday PM, June 25, 1998

Session U. Contacts to Wide Band Gap Semiconductors

Room: 009
Location: Olsson Hall

Session Chairs: Jerry Woodall, Purdue University; Ilesanmi Adesida, University of Illinois, ECE Department, Urbana-Champaign, IL 61801 USA

1:30 PM, U1

Correlation Between Chemical and Electrical Properties of n-GaN Schottky Interfaces: TAMOTSU HASHIZUME[1]; Yuji Koyama[1]; Hideki Hasegawa[1]; [1]Hokkaido University, Research Center for Interface Quantum Electronics (RCIQE) and Graduate School of Electronics and Information Engineering, Kita-13, Nishi-8, Sapporo, Hokkaido 060-8628 Japan

GaN is a promising semiconductor material for high-temperature and high-power electronic device applications as well as light-emitting device applications in blue/violet spectral regime. Significant progress has recently been made in growing high-quality GaN epitaxial layers, but considerable efforts are required in the area of processing techniques. Development of high-quality and stable Schottky contacts is important for realization of the GaN-based electronic devices. However, little is known about interface properties of metal/GaN contacts. In this paper, correlation between electrical properties of metal/n-GaN interfaces and chemical properties of surfaces and interfaces was systematically investigated by current-voltage (I-V), capacitance-voltage (C-V), x-ray photoelectron spectroscopy (XPS) and Raman spectroscopy methods. Si-doped GaN layers (n=$5x10^{16}$-$1x10^{17}$ cm^{-3}) grown on sapphire substrates by MBE and MOCVD were used. From the viewpoint of actual device fabrication process, surfaces were characterized after various wet surface treatments including cleaning processes and HF- and NH4OH- based etching processes. A series of high and low work function metals (Pt, Au, Ag and Al) was deposited onto the n-GaN surfaces by vacuum evaporation after these treatments. From the detailed XPS analysis of the Ga and N core-levels and O1s spectra, it was found that the samples treated only in organic solvents exhibited non-stoichiometric (Ga-rich) surfaces including large amounts of oxide and/or oxynitride components. Schottky contacts made on these surfaces clearly showed the presence of interfacial transition layer and a large discrepancy between the barrier heights obtained from the I-V and C-V methods. No dependence of barrier heights on metal work function was observed in these contacts. Significant decrease of the O1s intensity as well as the FWHM of Ga core-level was observed at the GaN surfaces after the etching in warm NH_4OH (50 ϒC) solution for 15min, indicating that this process is very effective in reduction of Ga oxide component. Almost all of the Schottky contacts formed on these surfaces showed nearly ideal thermionic emission characteristics with the ideality factors close to unity (n<1.1). Excellent agreements of Schottky barrier heights were obtained between C-V and I-V methods, reflecting the absence of near-surface modification of the band profile. Furthermore, the metal work function dependence of Schottky barrier heights was clearly seen after the NH4OH treatment, and the obtained slope parameter of 0.34 was found to be significantly higher than that predicted by Moench based on the metal-induced gap state (MIGS) model.

1:50 PM, U2+

Electronic Near-Surface Defect States Observed by Cathodoluminesence Spectroscopy In Mg-GaN Heterojunctions: A. P. YOUNG[1]; J. Schafer[2]; L. J. Brillson[3]; Y. Yang[4]; G. J. Lapeyre[4]; J. D. Mackenzie[5]; C. R. Abernathy[5]; [1]Ohio State University, Department of Electrical Engineering, Columbus, OH 43210 USA; [2]Ohio State University, Center for Materials Research, Columbus, OH 43210 USA; Ohio State University, Department Physics, Columbus, OH 43210 USA[3]; [4]Montana Sate University, Physics Department, Bozeman, MT 59717 USA; [5]University of Florida, Department of Materials Science and Engineering, Gainesville, FL 32611 USA

The electronic states at metal contacts to GaN are of significant concern for a wide range of microelectronic and optoelectronic device applications. Relatively little is known about the localized states at these junctions and their correlation with chemical interactions and interdiffusion. A metal of particular interest for such interface studies is Mg, because of its acceptor nature in GaN. Possible diffusion of this metal into the semiconductor may modify its effective doping level and thereby the effective Schottky barrier height. In this work, we study such a system before and after deposition of Mg by cathodoluminescence spectroscopy (CLS). Because the depth of excitation is a strong function of the incident electron beam energy of a few keV or less, this technique provides the capability to probe electronic defect levels localized both within a few nanometers of "buried" interfaces as well as within the junction constituents. Furthermore, the energies of CLS emission features can be related to the Fermi level stabilization of the Schottky contact. We have investigated the (0001) surface of n-GaN, grown by molecular beam epitaxy (SVT Associates) on sapphire with a Si donor concentration of $1x10^{18}$ cm^{-3}. Approximately 30monolayers of Mg were evaporated on the GaN surface in UHV. Prior to CLS studies, the specimens were characterized by soft x-ray photoemission spectroscopy (SXPS), documenting the metallic character of the overlayer and the Fermi level stabilization [1]. The Mg/GaN junction was then annealed at 1000 °C, aimed at inducing interdiffusion and p-type doping at the interface. The samples before and after the creation of the interdiffused Mg interface were studied by CLS., using e-beam excitation energies of 400 to 4000 eV and wide photon range detectors. For the n-GaN film, the dominant feature is the near-band edge luminescence at 3.4 eV. A second defect band extends from the "yellow" emission at ~2.3 eV down to 1.1 eV, with a peak at ~1.6 eV. For low beam energies, i.e. closer to the surface, the near-band edge luminescence decreases. For the heterojunction sample, the relative intensities of the two main features vary differently as a function of beam energy: while at high beam energies (4.0 keV) the luminescence pattern is identical with the bare GaN sample, a factor of four intensity increase of the deep defect band is observed for lower beam energy, at the expense of the near-band edge luminescence. This characteristic reaches its maximum at 1.0 KeV where the probe depth is of the order of 3–5 nm [2]. Sibseqiemt;u. at 500 eV the 1.6 eV peak decreases again. Therefore, this deep level emission is consistent with deep level formation at the Mg-GaN interface. Conversely, comparable emission of both undoped and bulk Mg-doped gaN provides no clear evidence for p-type doping. Significantly, SXPS shows Fermi level stabilization at 1.6 eV above the valence band, coincident with the peak in mid-gap emission. These results suggest that the annealing results in Mg indiffusion and deep level formation localized to the outer few atomic layers of GaN and which correlate with the Schottky barrier formation. [1] Y. Yang, S.H. Xu, G.J. Lapeyre, and J.M. van Hove, J. Vac. Sci. Technol., in press. [2] L. J. Brillson and R.E. Viturro, Scanning Microscopy 2, 789 (1988). This work was supported by the Department of Energy under grant DE-FG02-97ER45666.

2:10 PM, U3

Electrical Characteristics and Thermal Stability Of W, WSiN, Nb Contacts To p- and n-Type GaN: KENJI SHIOJIMA[1]; David T. McInturff[1]; Jerry M. Woodall[1]; Paul A. Grudowski[2]; Christopher J. Eiting[2]; Russell D. Dupuis[2]; [1]Purdue University, School of Electrical and Computer Engineering, 1285 Electrical Engineering Bldg., West Lafayette, IN 47907-1285 USA; [2]The University of Texas at Austin, Microelectronics Research Center, PRC/MER 10100 Burnet Rd., Bldg. 160, Austin, Tx 78712-1100 USA

A comprehensive annealing study of W, WSiN, and Nb refractory contacts to both p- and n-GaN was performed. The 1 μm-thick GaN films (p, n=$10^{17}$$cm^{-3}$) were grown on sapphire using metalorganic chemical vapor deposition. W or Nb was deposited by magnetron sputtering in an Ar plasma with a sputtering power of 350 W. The deposition of WSiN containing a saturated N content of 37 % also carried out by reactive sputtering in Ar and N mixture plasma with a sputtering power of 300 W. Samples were examined by I-V (current-voltage) measurements after isochronal annealing for 10 min. at temperatures up to 800 ϒC. Both W and Nb contacts to n-GaN showed rectifying characteristics with Schottky barrier heights ($q\phi_B$) of 0.63 eV, while the work functions of W and Nb are 4.55 and 4.3 eV, respectively. For p-GaN, the I-V curves showed very leaky behavior with a large series resistance (almost linear). In contrast, I-V curves of WSiN/n-GaN were very leaky while those of WSiN/p-GaN were rectifying with $q\phi_B$ of 0.8 eV. We propose that U-shape surface states induced during metal deposition could explain these reversible I-V characteristics. Assuming the bottom of the U-shape interfacial states (Ns) are located above mid-gap for the Nb and W contacts, because the interfacial state density is relatively

small close to the conduction band, Ns does not affect the I-V characteristics for n-GaN very much. For p-GaN, as the Ns are large close to the valence band, the current can go through the barrier via the interfacial states. This explains the very leaky I-V curves with a large series resistance. When the U-shape Ns are located below mid-gap, opposite I-V characteristics are expected as the WSiN contacts demonstrated. As for thermal degradation, Nb is very reactive with GaN and the interfacial mixing proceeds readily. The I-V curves of Nb/n-GaN degraded after annealing at 300 ϒC, and a spotty interfacial reaction was observed on the Nb dots upon annealing at 600 ϒC and the total thickness of Nb(45 nm-thick) was consumed. Because the formation energy of NbN(-235.1 KJ/mol) is smaller than that of GaN(-109.6 KJ/mol), the most likely reacted phase is NbN. No interfacial reaction was observed between W, WSiN and GaN up to 800 ϒC with an optical microscope, but the I-V characteristics degraded after annealing above 600 ϒC. W_2N could be formed at the interface upon high temperature annealing. The WSiN films with saturated N remain amorphous and WSiN/GaAs contacts show excellent I-V characteristics even after 800 ϒC annealing. Even though the WSiN film contains saturated N, N atoms could diffuse into the WSiN amorphous network because of the high vapor pressure of N on the surface of GaN. The refractory metal contacts to GaN have lower thermal stability than formed with GaAs.

2:30 PM, U4

Ohmic Contacts to p-GaN: HARI S. VENUGOPALAN[1]; John M DeLucca[1]; Suzanne E Mohney[1]; Robert F Karlicek[2]; [1]Pennsylvania State University, Materials Science & Engineering, 218, Steidle, University Park, PA 16802 USA; [2]EMCORE Corporation, 394 Elizabeth Avenue, Somerset, NJ 08873 USA

Improved ohmic contacts to p-GaN are needed for GaN-based laser diodes and light emitting diodes. In this study, six metallizations are compared for their suitability as ohmic contacts to p-GaN: sputtered Ni, Pt, Ni/Au, Ni/Pt, PtSi, and electrodeposited Pt. The Au/Ni/p-GaN contacts are frequently used in device fabrication, and Ni and Pt contacts have been reported before. However, the new metallizations Ni/Pt and electrodeposited Pt offer lower contact resistances, and PtSi offers superior thermal stability. For all the sputtered contacts, the I-V curves exhibited non-linearities that became less severe with annealing. The optimum annealing condition for Ni/p-GaN contacts was 5 min in N_2 at 400°C, and a specific contact resistance of 3.6 x 10^{-2} Ωcm^2 was measured at 10 mA. Ishikawa et al. have shown previously using high resolution transmission electron microscopy (HRTEM) that this annealing condition allows the Ni to penetrate the contamination layer on the GaN prior to metallization, resulting in an intimate contact. A similar specific contact resistance of 3.4 x 10^{-2} Ωcm^2 was measured for the Au/Ni/p-GaN contact. However, the lowest specific contact resistance (1.5 x 10^{-2} Ωcm2) among the sputtered contacts was obtained for Pt/Ni/p-GaN after a 1 min anneal at 600°C. Auger depth profiles reveal the formation of a Ni-Pt solid solution in contact with GaN at this annealing temperature. We postulate that the higher work function of Pt and the Ni-Pt solution, as compared to that of Ni and Au, is responsible for the lower resistance of the Pt/Ni/p-GaN contacts, while Ni is beneficial because it can penetrate the contamination layer on GaN, creating a more intimate contact. Since Pt has a higher work function than Ni, we might expect the Pt/p-GaN contacts to exhibit the lowest specific contact resistance. However, the specific contact resistance of the sputtered Pt contacts was greater than that of the Ni/Pt contacts for all samples and annealing conditions examined. Since Pt is believed to be less effective at dispersing the native oxide on the semiconductor, we sought another method, electrodeposition, to achieve intimate Pt/p-GaN contacts. Platinum contacts were deposited on p-GaN in an acidic bath in which gallium oxide is soluble. For these Pt/p-GaN contacts, the I-V curves displayed only very minor non-linearity, and a specific contact resistance of 9.7 x 10^{-3} Ωcm^2 was measured after a 5 min anneal at 400°C. Unlike the sputtered Pt films, we anticipate that the electrodeposited Pt is in more intimate contact with GaN. HRTEM is underway to confirm this hypothesis. The morphology and thermal stability of ohmic contacts to p-GaN were also studied. Although Ni, Pt, and Ni/Au contacts form islands upon annealing above 700°C, PtSi contacts were morphologically and electrically stable for short anneals up to 1000°C.

2:50 PM, U5

Effects of Annealing Ambience on Electrical Properties of Metal Contacts to p-GaN: YASUO KOIDE[1]; T. Maeda[1]; S. Fujita[1]; Masanori Murakami[1]; T. Uemura[2]; T. Uemura[2]; N. Shibata[2]; [1]Kyoto University, Dept. of Materials Science and Engineering, Sakyo-ku, Kyoto 606-8501 Japan; [2]Toyoda Gosei Co., Ltd., Technical Deptartmet of Optelectronics, 30, Nishinomachi, Kitajima-cho, Inazawa, Aichi 492-8540 Japan

GaN-based semiconductors are widely used in experimental diodes (LDs and LEDs) emitting blue or ultraviolet lights. One of the major problems to manufacture these diodes is lack of low resistance Ohmic contact materials for p-GaN. Various approaches have been made to develop such low resistance Ohmic contact materials to improve the device performance and reliability. Recently, Shibata et al.[1] studied the effect of annealing ambience on the electrical properties of Ohmic contact to p-GaN, and found that annealing in an ambience containing O_2 reduced the contact resistance. However, the reason for this improvement was not understood. In the present paper, the effects of annealing in a N_2/O_2 ambience on the electrical properties of Ohmic contacts to the p-GaN were investigated to obtain a guideline to reduce the contact resistance. Ni/Au, Co/Au, Pd/Au, and Pt with large work functions were selected as the contact materials, because the lower contact resistance at the p-GaN/metal interface was obtained with increasing the metal work functions [2]. Undoped GaN and Mg-doped p-GaN epilayers (which were used as the substrates) were successively grown by MOVPE on the sapphire substrates using thin AlN buffer layers. The thicknesses of undoped and doped layers were 1.5 and 0.5 μm, respectively. The hole concentrations of the p-GaN epilayers were 4-7x10^{17}cm^{-3}. The contact metals were deposited on the GaN substrates in an electron beam evaporator with a base pressure lower than 5x10^{-7} Torr. The GaN/metal samples were annealed at temperatures below 600 ϒC in N_2/O_2 mixed gas, where the N_2/O_2 ratios were changed. Microstructures at the p-GaN/metal interfaces were analyzed by x-ray diffraction and high-resolution electron microscopy. The contact resistances were measured by a circular transmission line method [2]. The specific contact resistances, ρ_c, of all contacts were reduced by a factor of 2 - 3 when the contacts were annealed in the N_2/O_2 ambience at temperatures of 500 ~ 600 ϒC, compared with those annealed in N_2 gas. The typical ρ_c value was 2 - 5x10^{-3} Ωcm^2 for the Ni/Au contact. This indicated that annealing in the ambient containing O_2 at elevated temperatures provided the reduction of the contact resistance. The microstructural analysis at the p-GaN/metal interface was carried out to explain the reduction of the contact resistance. The present results concluded that annealing in oxygen ambience increased the acceptor concentration in the GaN epilayers close to the contact interface by reactivating the Mg acceptors passivated by hydrogen. Therefore, reduction of the ρ_c values in the N_2/O_2 ambience was due to improvement of the electrical properties of the GaN substrate rather than formation of an intermediate semiconductor layer with low energy barrier or high doping density. [1]N. Shibata, J. Umezaki, M. Asai, T. Uemura, T. Kozawa, T. Mori, and T. Owaki, Japanese Unexamined Patent No. 09064337A. [2]H. Ishikawa, S. Kobayashi, Y. Koide, S. Yamasaki, S. Nagai, J. Umezaki, M. Koike, and M. Murakami, J. Appl. Phys. 81, 1315 (1997).

3:10 PM Break

3:30 PM, U6

Processing and Characterization of Ti And TiN Contacts to n-GaN: BRAIN P. LUTHER[1]; Suzanne E. Mohney[1]; Thomas N. Jackson[2]; [1]The Pennsylvania State University, Dept. of Material Science and Engineering, 220 Steidle, University Park, PA 16802 USA; [2]The Pennsylvania State University, Dept. of Electrical Engineering, 121 E.E. East, University Park, PA 16802 USA

Ti and TiN-based contacts have been examined to elucidate the role of process variables on the phase formation, specific contact resistance, and current conduction mechanisms in these contacts. Ti (150nm), TiN (200nm), and Ti/TiN (5nm/200nm) contacts were fabricated on n-type GaN (Si-doped 7x10^{17} cm^{-3}, 44 Ω / square) and characterized by specific contact resistance measurements and by x-ray photoelectron spectroscopy depth profiling. Ti contacts were annealed between 400 and 900 ϒC in Ar and N_2 to observe the effects of the annealing environment on ohmic contact formation. Ti contacts annealed in N_2 became ohmic after 1 min at 700 ϒC and reached a minimum specific contact resistance of 4x10^{-6} Ω cm^2. However, Ti contacts needed to be annealed in Ar for 20-25 min at 700 ϒC to become ohmic. These contacts also reached a minimum specific contact resistance of 4x10^{-6} Ω cm^2. Depth profiles showed that TiN was present at the contact/GaN interface whenever annealed Ti contacts (either in Ar or N2) exhibited ohmic characteristics. Evidence of interfacial reaction between the Ti and GaN was obtained in each case, although the extent of the reaction was influenced by the annealing environment. TiN and Ti/TiN contacts were also examined. These contacts were annealed between 400 and 800 ϒC in Ar. TiN contacts became ohmic after 1 min at 400 ϒC but reached a minimum specific contact resistance of only of 3x10^{-5} Ω cm^2 after

being annealed at 800 ϒC. Ti/TiN contacts became ohmic after being annealed for 1 min at 700 ϒC, similar to Ti contacts annealed in N2, and reached a minimum specific contact resistance of $6x10^{-6}$ Ω $cm^{2.}$ TiN ohmic contacts annealed in Ar displayed higher specific contact resistance when measured at 77K than at room temperature (characteristic of thermionic or thermionic-field emission), while Ti/TiN and Ti contacts annealed in Ar showed no temperature dependence (characteristic of field emission). TiN contacts are not expected to react with GaN based on the thermodynamics. Ti/TiN and Ti contacts react with the GaN during contact annealing, resulting in the formation of TiN at the interface. Therefore, the reaction (or lack of reaction) between Ti and GaN during contact annealing appears to correlate with the current conduction mechanism. Based on the results of this study, we conclude that having TiN in intimate contact with n-type GaN is necessary for these contacts to become ohmic. When the TiN was formed by a reaction between Ti and GaN during the contact anneal, the current conduction mechanism of field emission dominated and allowed the contacts to reach a lower specific contact resistance.

3:50 PM, U7

Evaluation of Ohmic Contacts on SiC Formed by YAG Laser Irradiation: YORITO OTA[1]; [1]Matsushita Electronics Corporation, Electronics Research Laboratory, 3-1-1 Yagumo-nakamachi, Moriguchi, Osaka 570, Japan

Ohmic contacts on n-type SiC have been formed with YAG pulse laser irradiation at room temperature and evaluated with a microscope photograph, transmission line method (TLM) and Auger electron spectroscopy (AES). The novel ohmic formation method is a thermally unequivalent process using a high-power YAG laser which has wavelength of 1060 nm, pulse width of 8 nsec, and power density of 30 J/cm^2 [1]. The wavelength is fairly longer than the bandgap of SiC, so that the metals on SiC substrate are selectively heated and alloyed. The new technique realizes ohmic contacts easily on SiC surface without the contact pattern deformations caused by high temperature treatments [2]. The ohmic metals used in this study are Ti, Ni, Pt, and Au, each formed on an n-type ($4.2 X 10^{18}$ cm^{-3}) 6H-SiC epitaxial layer. Good surface morphology with small grain size and low contact resistivity are obtained with Ti and Pt. The lowest contact resistivity ($4 X 10^{-5}$ ohm-cm^2) is obtained for Ti, which diffuses into the SiC layer to a depth more than 300 nm, when evaluated with AES. It is supposed that the interface between Ti and SiC changes to Ti-related alloy, where the interface temperature rises more than 700 ϒC during the pulse laser irradiation. The developed pulse laser alloying technique is easily applicable to device formations. In this study, we fabricated a lateral Schottky diode. The metals for the Schottky contact and the ohmic contact were simultaneously formed by Ti evaporation and then one metal was alloyed with shaped-laser irradiations at room temperature. The size of Schottky electrode was 0.02 mm square. The fabricated diode exhibited good I-V characteristics with a low resistive forward-biased curve and a high breakdown (>10V) reverse-biased curve. Excellent ideality factor n = 1.1 was obtained from Gummel plot. A novel pulse laser alloying technique has been investigated using a high-power YAG laser in order to realize ohmic contacts on SiC at room temperature. The new method exhibits very low contact resistivity around $4 X 10^{-5}$ ohm-cm^2 with Ti metal diffused into SiC layer by the laser irradiation. This simple but effective method promises to contribute greatly to the progress of SiC device fabrication.

4:10 PM, U8

The Process of Ohmic Contact Formation to p-Type 6H-SiC by Focused Ion Beam Surface-Modification.: AGIS A. ILIADIS[1]; S. N. Andronescu[1]; K. Edinger[1]; J. H. Orloff[1]; R. D. Vispute[2]; V. Talyansky[2]; T. Venkatesan[2]; M. C. Wood[3]; K. A. Jones[3]; [1]Electrical Engineering Department, University of Maryland, College Park, MA 20742 USA; [2]Center for Superconductivity Research, Department of Physics, University of Maryland, College Park, MA 20742 USA; [3]Army Research Laboratory, 2800 Powder Mill Road, Adelphi, MA 20783 USA

The process of ohmic contact formation in p-type 6H-SiC by focused ion beam (FIB) surface-modification and in-situ direct-write or ex-situ metal deposition is examined in order to identify the parameters critical to minimizing contact resistance values. Surface-modification using focused Ga ion beams is aiming at lowering surface barriers by increasing surface disorder, while also increasing SiC surface doping by the incorporation of Ga ions to enhance tunneling and further improve contact resistance. In order to develop an understanding of the parameters involved in the process, Pt was in-situ direct-write deposited on surface-modified p-type (10^{19} cm^{-3}) 6H-SiC, and compared with Pt and TiN metallizations deposited ex-situ by pulsed laser deposition (PLD) on the same substrates. Both amorphous (room temperature) and epitaxial (600 C) metal films were deposited by laser (KrF Excimer) ablation from a target in a high vacuum PLD system. Transmission line (TLM) contact resistance measurements, and analytical techniques including Auger electron spectroscopy (AES), secondary ion mass spectroscopy (SIMS), atomic force microscopy (AFM), and transmission electron microscopy (TEM), indicate that the contact formation by surface-modification is a two step process of surface disorder and Ga incorporation, each step presenting an optimum window of FIB parameters such as ion energy and dose. For minimum contact resistance values, focused ion beam energy is found to be at a moderate level of 20 KeV, and the Ga dose between 10^{15} and $10^{17}cm^{-2}$, with varying dose window for different metals. Pt, for example, has a dose window for minimum contact resistance between 10^{15} and $10^{16}cm^{-2}$, while TiN has a dose window between 10^{16} and $10^{17}cm^{-2}$, an order of magnitude higher. Contact resistance values were between 10^{-3} and 10^{-5} Ωcm^2. These values from as-deposited contacts were comparable to or better than contact resistance values from conventionally deposited and annealed p-type contact systems. Further factors affecting the contacts are discussed in the context of the quality of the deposited metals. In general epitaxially deposited metals by PLD resulted in better quality contacts, while the direct-write deposited contacts showed significant C impurity incorporation. The effects of post-deposition annealing to the interface and contact resistance will be discussed.

4:30 PM, U9+

The Effect of Reactive Ion Etching on Schottky Barriers on 4H-SiC Surfaces: VISHNUI K. KHEMKA[1]; T. P. Chow[1]; R. J. Gutmann[1]; [1]Rensselaer Polytechnic Institute, Center for Integrated Electronics, CII-6015, 110, 8th Street, Troy, NY 12180-3590 USA

Silicon carbide is a promising material for devices operated at high-voltages, high-temperatures and/or high-frequencies. Several research groups have fabricated and reported three terminal microwave SiC MESFETs and SITs. These microwave devices utilize a Schottky metal gate contact typically formed on trenches or recess areas formed by reactive ion etching (RIE). The damage created during the dry etching processes can have significant effect on the device performance. In this paper we have investigated, for the first time, the effect of RIE induced damage on 4H-SiC surfaces etched in fluorinated plasmas using Ni Schottky diodes and analytical techniques (XPS,SIMS). The diodes have been characterized using current-voltage current-voltage-temperature and capacitance-voltage measurements. The Schottky diode were fabricated on commercial 4H-SiC n/n^+ wafers. The thickness and doping of the epitaxial layer and the substrate were 3.5 micron, 9.7E15 cm^{-3} and 287 micron, 7.2E18 cm^{-3} respectively. Schottky diodes (100, 200, 300 and 400 micron diameter) were fabricated following a standard clean and sacrificial oxidation, by e-beam evaporation of Ni through a shadow mask. The reactive ion etch analysis samples were etched in three different fluorinated plasmas (CHF_3+O_2, CF_4+O_2 and CHF_3+CF_4) prior to the shadow mask evaporation of Ni on the front side. Ni based metallization was utilized to form the backside ohmic contact. Etch rate of 4H-SiC for these three plasma chemistries have also been characterized. The control (unetched) diodes were characterized with near ideal forward characteristics (n=1.07, ϕ_B=1.47 eV) and forward current density as high as 9000 A/cm^2 with low forward drops. High current handling capability was observed in diodes with etched surfaces as well, however, a decrease in barrier height and increase in ideality factor was obtained. Diodes with surfaces etched in CHF_3 showed a more severe degradation in forward characteristics compared to diodes etched in CF_4+O_2 plasma. Richardson's constant, extracted from I-V-T measurements, was 140 A/cm^2.K^2 for the control diodes and 39 A/cm^2.K^2 for the diodes etched in CF_4/O_2 plasma. Specific on-resistance as low as 5E-4 Ω.cm^2 was measured. The degradation in forward characteristics of the diodes with etched surfaces is a direct consequence of damage creation and/or polymer deposition during RIE. The reverse leakage current of the diodes was analyzed as a function of temperature and device diameter. Edge dominant leakage current was observed up to about a reverse bias of 25 V beyond which bulk leakage current dominates. On comparison with control diodes and CF_4+O_2 etched diodes, significant improvement in the leakage current was observed for the diodes with surfaces etched in CHF_3+O_2 and CHF_3+CF_4 plasmas. Interfacial thermionic emission model has been utilized to analyze the reverse characteristics of these diodes. Reverse breakdown voltage of 350 V was measured at a reverse current density of 1 A/cm^2 on control diodes. No improvement in the breakdown voltage was obtained for the diodes with surfaces etched in CHF_3+O_2 and CF_4+O_2 whereas the breakdown voltage improved significantly for the CHF_3+CF_4 etched diodes. This study demonstrates the effect of RIE on the performance of Ni/4H-SiC Schottky diodes which in turn can have significant impact on SiC microwave devices where Schottky contacts are utilized as

basic building blocks. Selection of appropriate RIE process involves a trade-off between SiC etch rate and reverse characteristics of Schottky contacts. The authors gratefully acknowledge the support of this work by Philips Research Laboratories and MURI of the Office of Naval Research.

4:50 PM, U10+

Ohmic Contacts to n-Type and p-Type ZnSe: M. R. PARK[1]; W. A. Anderson[1]; M. Jeon[2]; H. Luo[3]; [1]State University of New York at Buffalo, Department of Electrical and Computer Engineering, 217 Bonner Hall, Amherst, NY 14260 USA; [2]Samsung Advanced Institute of Technology, Photonics Lab., Materials Sector, PO Box 111, Suwon, Kyung-gi Do 440-600 Korea; [3]State University of New York at Buffalo, Department of Physics, 126 Fronczak, Amherst, NY 14260 USA

Stable Ohmic contacts are essential for reliable operation of electronic devices. Such contacts have been made to n-type and p-type ZnSe. Au, Pd, Cu and Se for p-type N-doped ZnSe($1x10^{17}$ cm^{-3}) and AuGe, In, Yb and Mg for n-type Cl-doped ZnSe ($4.5x10^{18}$ cm^{-3} and $1.15x10^{19}$ cm^{-3}) grown by molecular beam epitaxy (MBE) on (100) semi-insulating GaAs substrates have been deposited by thermal evaporation. Annealing techniques at different temperatures, chemical etching and cleaning prior to metallization and reactive ion etching (RIE) in a N2 plasma and a Ar plasma for p-ZnSe have been studied. The electrical characteristics for the contacts were examined by the current versus voltage curves and the specific contact resistance was determined by use of the transmission line method (TLM). The current transport mechanisms for the Mg/Au contact to n-type ZnSe and the Cu/Au contact to p-type ZnSe have been studied by the current versus voltage for different temperatures (I-V-T) measurements. In/Au was best for n-type and Cu/Au for the p-type materials. Using a Br etching solution prior to metallization did not produce any measurable improvement but instead reacted with the photoresist and caused failure during patterning of the sample. Plasma treatment of the ZnSe surface prior to metallization was proven to lower the contact resistance to p-type ZnSe. The lowest specific contact resistance values of $1.67x10^{-1}$ Ωcm^2 for the Cu/Au contact to p-type ZnSe with a N2 plasma treatment and $1.04x10^{-2}$ Ωcm^2 for the In/Au contact to n-type ZnSe were achieved. Two different current flow mechanisms were shown for the Cu/Au contact to low doped p-ZnSe ($1x10^{17}$ cm^{-3}) and three for the Mg/Au contact to highly doped n-ZnSe ($1.15x10^{19}$ cm^{-3}). The Cu/Au contact to p-ZnSe and Mg/Au contact to n-ZnSe have been observed to be especially stable and reproducible.

Thursday PM, June 25, 1998

Session V. Templated and Ordered Growth of Quantum Structures

Room: E316
Location: Thornton Hall

Session Chairs: Jim Merz, University of Notre Dame, Notre Dame, IN 46566; Eli Kapon, Swiss Federal Institute of Technology (EPFL)

1:30 PM, V1

Effects of the Growth Condition on the Selective Alignment of InAs Quantum Dots on Patterned GaAs (100) Substrates: RUTH ZHANG[1]; RAYMOND TSUI[1]; Kumar Shiralagi[1]; Herb Goronkin[1]; [1]Motorola, Inc., Phoenix Corporate Research Laboratories, 2100 East Elliott Road, EL308, Tempe, AZ 85284 USA

Self-organized quantum dots (SOQDS) formed in the Stranski-Krastanov growth mode have been attracting significant interest because of their potential for realizing novel optoelectronic and single-electron devices. To fabricate such devices using nanoscale dots, one needs to have good control over the size distribution, density, and position of the SOQDS. This is difficult to achieve on a planar substrate, however. Recently, we reported the growth of InAs SOQDs on patterned substrates using selective area epitaxy, and demonstrated the ability to spatially control the positioning of the SOQDS [1]. In this paper we investigate the selective formation, under different growth conditions, of InAs SOQDs on top of GaAs mesa stripes on patterned substrates, and show the feasibility of self-alignment of SOQDs by the proper choice of growth condition and mesa width. GaAs (100) substrates were patterned by conventional lithography, utilizing SiO_2 as the mask material. Windows were opened in the SiO_2 in the form of stripes aligned along the major crystallographic directions. Chemical beam epitaxy was used for the selective growth of the GaAs buffer layer and the InAs SOQDS, using triethylgallium, trimethylindium and arsine as the source materials. The structure typically consists of a 400-nm thick GaAs buffer layer and less than 2 ML of InAs deposition on top. The GaAs buffer layer was grown at 625 °C, and forms mesa stripes with (100) top facets and side facets of various orientations. The width of the (100) top facet is a function of the window width in the SiO_2 and the crystallographic alignment of the stripe. The InAs was deposited at 520 °C, but different V/III flux ratios were used for various growth runs. The samples were characterized by scanning electron microscopy and atomic force microscopy. The SOQDs are formed only on the top facets. It is found that, for a fixed V/III ratio, the spatial distribution of the SOQDs becomes increasingly uniform as the top facet width is reduced below 250 nm. In fact, by properly reducing the width to sub-200-nm dimensions, well-aligned arrays consisting of one, two, or three rows of SOQDs are demonstrated for mesa stripes aligned in the [010] direction. Furthermore, for top facets with similar widths, non-uniformity in the SOQD distribution increases with V/III ratio. The effects of In adatom migration, facet width, V/III ratio, and pattern orientation on the controlled formation and alignment of SOQDs will be presented. [1] R. Tsui, R. Zhang, K. Shiratagi, and H. Goronkin, Appl. Phys. Lett. 71 (22), 3254 (1997).

1:50 PM, V2

Growth of Self-Assembled InAs Dots and Quantum Wire Structures on Patterned: KANJI YOH[1]; Ryusuke Nakasaki[1]; Shingo Takabayashi[1]; [1]Hokkaido University, Research Center for Interface Quantum Electronics, N13, W8, Kita-ku, Sappporo, 060-8628 Japan

We have investigated the MBE growth of self-assembled InAs quantum dot and GaAs/AlGaAs quantum wire structures on patterned (311)A GaAs substrates. We have found that the self-assembled InAs dots were found to grow selectively on the slopes inclined toward (100) facet but not on surfaces inclined to (111)A, such as (311)A, (211)A or (111)A. Present results and our previous results of facet preferential growth of InAs dots were found to be explained by planar 2D growth tendency of strained InAs layer on gallium stabilized surfaces and 2D growth tendency on arsenic stabilized surfaces. At the moment, planar 2D growth tendency of strained InAs layer on (111)A (gallium stabilized surface) is explained [Yamaguchi,1997] by the formation of misfit dislocations at the boundaries of coalescing strained islands at the initial stage of strained InAs growth. It suggests that the self-assembled InAs dot formation mechanism on various facets should be discussed by Stranski-Krastanow growth mode not only with simple strain discussions, but also with misfit dislocation patterns at the initial stage of the strained InAs growth on GaAs. Apart from the selectivity discussions on definite facets, we have also observed that the InAs dots are selectively formed along the narrow stripes which are a few degrees off from definite facets, such as (311)A. It also suggests to take account of atomic step densities of misoriented surfaces in addition to atomic bond energy with surface atomic rearrangements at definite low index surfaces. Gallium stabilized and arsenic stabilized surfaces are also known to incorporate amphoteric dopants into gallium and arsenic sites, respectively. Making use of this mechanism, lateral p-n-p structure have been reported previously [Saito,1993] [Arnone 1996], but the reported wire widths were more than a micron. We have investigated etching and overgrowth conditions on various substrate orientations in order to fabricate quantum wires based on selective doping. We have successfully fabricated quantum wires basically in lateral n-i-p-i structures and confirmed the quasi-one-dimensional confinement of electrons at the GaAs/AlGaAs heterointerface. The widths of the quantum wires fabricated on (311)A substrates range between 3000 angstroms and 500 angstroms. The heterojunction lateral n-i-p-i structure was verified by Electrostatic Force Microscope and Cathode Luminescence. Although electron mobilities were low because of the shallow (500 angstroms) buffer layer, the effective mobility of the quantum wire transistor turned out to be $300cm^2/Vs$ which is about 60% of the Hall mobility performed on a reference sample with (100) facet grown at the same time as the quantum wire structures. Much higher effective mobilities of 1200cm2/Vs(300K) and $5800cm^2/Vs$ (77K) in ridge quantum wire transistors based on (100) substrates suggests higher mobilities of quasi-one-dimensional structures are expected by employing a thicker buffer layer in the structures based on (311)A substrates.

2:10 PM, V3

Molecular Beam Epitaxy Growth of Self-Assembled InAs Dots on Si: P. C. SHARMA[1]; Kevin W Alt[1]; John Yeh[1]; Dawen Wang[1]; Kang L Wang[1]; [1]University of California, Los Angeles, Device Research Laboratory, Department of Electrical Engineering, Los Angeles, CA 90095-1594 USA

Fabrication of self-assembled quantum dots (QDs) has become the subject of continued research efforts due to the potential of quantum dot structures in electronic and optoelectronic device applications. So far, InAs/GaAs and Ge/Si heterostructures have been extensively used to realize self-assembled dot structures. With its established suitability for device applications and a thermal expansion coefficient value ($4.68x10^{-6}$ K-1) close to that of InAs (4.7x10-6K-1), silicon is a promising substrate for the growth of InAs dots. In the present work, we report on the growth of InAs dots on Si using molecular-beam epitaxy (MBE). The morphology of the samples is determined by using atomic force microscopy(AFM). Samples grown under the same deposit on conditons and different InAs coverages have shown formation of uniform islands (size 25 nm; height 9 nm) with sharp lateral size distributions and high densities. After an initial rapid increase, the dot sizes are found to increase steadily with InAs coverage until coalescence while their heights show a slower increase. The dot density increases from $1.0x10^{11}cm^{-2}$ to $6.6x10^{12}$ cm^{-2} during the initial stages of dot formation and decreases back to $1.1x1\ 0^{11}cm^{-2}$ as coalescence sets in. The interdot distances indicate a near random spatial distribution of these dots. These observations are found to be consistent with the present understanding of the strain relaxing mechanisms in heteroepitaxial systems with a large lattice mismatch. During the growth of InAs on Si, the strain due to the large lattice mismatch (~11.5 %) is partially relieved by the formation a high density of dislocation-free islands which undergo anelastic deformation. The additional strain due to the further deposition of InAs leads to the formation of misfit dislocations resulting in a transition of coherently strained islands to relaxed islands. These relaxed islands then grow very rapidly and coalesce to produce continuous three dimensional InAs film. Although only coherent islands are considered suitable for applications because of the uniformity in their size, our studies demonstrate the possibility of retaining narrow and uniform size distributions for the three dimensional island seven beyond the formation of relaxed islands.

2:30 PM, V4

Structure and Photoluminescence of Single AlGaAs/GaAs Quantum Dots Grown in Pyramidal Recess Substrate Patterns: ARNO HARTMANN[1]; YANN DUCOMMUN[1]; Laurent Loubies[1]; Eli Kapon[1]; [1]Swiss Federal Institute of Technology-EPFL, Department of Physics, Institute of Micro- & Optoelectronics, CH-1015 Lausanne Switzerland

We show that organo metallic chemical vapor deposition of AlGaA/GaAs on patterned substrates is a powerful technique for the controlled fabrication of quantum dots (QD). The substrate patterns, which control the position of individual QDs, are triangular pyramidal recesses etched into {111}B oriented GaAs substrates. The growth parameters bike GaAs quantum well (QW) growth time and growth temperature are used to define the QD thickness or modify its shape respectively. Using cross sectional atomic force microscopy (X-AFM), we are able to study the three-dimensional growth evolution inside the pyramidal holes. We find that deposition of AlGaAs results in straight pyramid sidewall facets that form sharply defined corners with self limited radii of curvature in the 10 nm range. During the deposition of the GaAs QW layer, lateral segregation of Ga leads to a rounding of these sharp corners and therefore gives rise to the formation of GaAs quantum Wires (QWR) along the corners and a GaAs QD at the pyramid tip, where the three corners meet. Detailed X-AFM investigations allow the determination of the thickness ratio between the GaAs QW on the sidewalls, the QWRs along the corners, and the QD at the pyramid tip to be 1:3:6. During AlGaAs deposition, a similar Ga segregation results in a vertical Ga-rich AlGaAs QWs along the corners which meet at the pyramids center forming a vertical Ga-rich AlGaAs QWR at this position. AlGaAs deposition also leads to the recovery of the radius of curvature to its small, self-limited value, enabling the vertical stacking of identical QD structures. We use a microphotoluminescence (μPL) setup with a laser diameter <1μm to study the optical properties of single pyramidal structures. Such μPL spectra of single pyramids exhibit three distinct peaks which we attribute (based on their energetic positions) to transitions originating from the QWs, QWRs and the QD. Different additional experimental results such as selective excitation of different parts of a single pyramid or μPL of incomplete pyramids at a cleaved edge as well as the excitation power dependence of the different transitions confirm this identification of the peaks. The transitions observed from single QDs consistof several lines with widths of typically 0.2 to 1.5 meV depending on the excitation power. The transitions of different single QDs across the sample display different fine structures but fall within a narrow energetic window of approximately 15meV, demonstrating the highstructural uniformity over mm- distances achievable with our technique. For samples with different nominal GaAs QW thickness, we observe a systematic energetic shift of the QD-transitions. We can therefore easily control the QD thickness by variation of the GaAs growth time.

2:50 PM, V5

Formation and Lateral Carrier Confinement of Triangular-Shaped Dot-Like Structures Grown By Molecular Beam Epitaxy on Patterned GaAs (311)A Substrates: ZHICHUAN NIU[1]; Richard Nitzel[1]; Uwe Jahn[1]; Hans-Peter Schinherr[1]; Jerg Fricke[1]; Lutz Deweritz[1]; Klaus H. Ploog[1]; [1]Paul-Drude-Institute für Festkörperelektronik and Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China, Hausvogteiplatz 5-7, D-10117, Berlin Germany

Highly ordered triangular-shaped dot-like (TD) structures are grown by molecular beam epitaxy on GaAs (311)A substrates patterned with square-shaped holes. Atomic force microscopy and scanning electron microscopy shows that the TD structures are formed freely between the holes due to preferential migration of Ga adatoms from the sidewalls of the holes to the top surface. The low-temperature cathodoluminescence emission centered at 783 nm, 772 nm and 767 nm correspond to three distinct regions of the TD structure identifying lateral energy barriers around the top portion of the TD structure induced by variations of the QW width. The micro-photoluminescence spectroscopy further show well resolved peaks originating from the three portions of the TD structure indicating a lateral energy barrier of 13 meV between the top portion and the nearby smooth regions with efficient radiative recombination. The formation of the TD structure is a promising method to realize three-dimensionally confined nanostructures in a controlled manner.

3:10 PM Break

3:30 PM, V6

Spatial Ordering of Self-Organized InGaAs/AlGaAs Quantum Disks on GaAs (311)B Substrates: EIICHI KURAMOCHI[1]; Jiro Temmyo[1]; Hidehiko Kamada[2]; Toshiaki Tamamura[1]; [1]NTT, Opto-electronics Labs., 3-1 Morinosato Wakamiya, Atsugi, Kanagawa 243-0198 Japan; [2]NTT, Basic Research Labs., 3-1 Morinosato Wakamiya, Atsugi, Kanagawa 243-0198 Japan

We already reported novel self-organized formation of strained InGaAs/AlGaAs quantum disks on GaAs (311)B substrates, where disk-shaped well part is automatically covered with Al(In)GaAs barrier material[1-2]. Our quantum disks are characterized by the some clear ordering among disks and excellent optical activities, but, due to the spontaneous formation the ordering is far from the perfect one, which may cause large size fluctuation, and may limit the electronic device application. We recently developed new technology to define the position of self-organized quantum disks by using buried fine SiN dots, and realized perfect spatial ordering among disks[3]. In this work we studied the size fluctuation of position-defined disks, and the In content effect on the spatial ordering. The size fluctuation was evaluated by AFM measurements of the surface of doubly stacked $In_{0.3}Ga_{0.7}As$/AlGaAs quantum disks. In the perfectly spatially ordered 250-nm-pitch disk arrays, the standard deviation of height and base-width of quantum disks, calculated from all 366 disks in a 5000-nm * 5000-nm AFM image without screening, is less than 2 nm and 10 nm (average height/ base-width = 22 nm / 140 nm), respectively. These values are less than 1/3 in non-patterned area, indicating the potential of our technology for solving inhomogeneous broadening issue. In this work, we also studied the In content of the spatial ordering phenomena. In the position-defined disk formation, we found clear SiN pitch dependence upon ordering degree. The optimum pitch for nominal $In_{0.3}Ga_{0.7}As$ is in the range of 250-300 nm. Then, we changed the In content, that is, amount of strain, and found that the optimum pitch is reduced with the increase of In content. The spatial ordering of $In_{0.4}Ga_{0.6}As$ disks became the best at a pitch of 150 nm. This means that the disk density can be controlled by In content and be improved by using larger strain system which is also preferable for optical device application. REFERENCES1 R. Notzel, J. Temmyo, and T. Tamamura; Nature 369 131 (1994). 2 R. Notzel, J. Temmyo, and T. Tamamura; Jpn. J. Appl. Phys. 33 L275-L278 (1994). 3 E. Kuramochi, J. Temmyo, T. Tamamura, and H. Kamada; Appl. Phys. Lett. 71 1655 (1997) [Errata; 71 3448 (1997)].

3:50 PM, V7

Self-Ordering and Quantum Confinement in InGaAs/(Al)GaAs V-Groove Quantum Wires: E. MARTINET[1]; C. Constantin[1]; G. Biasiol[1]; K. Leifer[1]; A. Rudra[1]; F. Reinhardt[1]; E. Kapon[1]; [1]Swiss Federal Institute of Technology-EPFL, Department of Physics, Institute of Micro & Optoelectronics, CH1015 Lausanne Switzerland

The growth of InGaAs/(Al)GaAs heterostructures on V-groove substrates by low pressure organometallic chemical vapor deposition results in the self-ordering of crescent shaped quantum wires (QWRS) with distinct nano-facets. The strain enhances a monolayer step-bunching along the {3 1 1}A facets, resulting in an additional faceting of the QWR along the wire axis. This longitudinal modulation is periodic (a few nm high over a ~50nm period) and could be useful for 3D confinement of carriers in aligned chains of quantum dots which self-form at the bottom of the V-groove for high In compositions. We used transmission electron microscopy to study the dependence upon growth temperature of the InGaAs/GaAs QNW profile. Low temperatures (550ϒC) result in smaller facets at the lower QWR interface and in a larger segregation of In adatoms in the center of the QWR, yielding larger quantum confinement effects. InGaAs/GaAs QWRs have also been grown on 0.25 μm pitch corrugations in order to allow for dense lateral QWR arrays and two-step growth process suitable for the realization of devices combining carrier and photon confinement. This allowed us to demonstrate high quality microcavities incorporating V-groove QWRS. Photoluminescence (PL) of InGaAs/AlGaAs QWRs with y < 0.35 showed intense emission from the wires and narrow linewidths, an evidence for efficient carrier capture through the AlGaAs VQW and good uniformity along the wire. InGaAs/GaAs QWR arrays on 0.25 μm pitch corrugations showed state of the art linewidths (as low as 7.6 meV) and efficient capture from the side QWs, owing to a carrier diffusion length larger than the pitch. At high excitation densities, several quasi-one dimensional QWR subbands appear as a result of bandfilling, presenting virtually no energy shifts (< 2 meV), even when several (⊕ 3) subbands are filled. This is interpreted as due to the enhanced exciton stability owing to the 2D quantum confinement, even in the presence of strain effects. The PL excitation spectra of a series of InGaAs/AlGaAs QWRs "with increasing In mole fraction" were measured in order to study the effects of strain and 2D-confinement on the optical properties of the QWRS. A strong modification of the optical anisotropy due to strain was observed. This was explained by a strain-induced splitting of the heavy-bole (hh) and light-hole (lh) valence band edges, resulting in a decoupling of hh and lh subbands, as opposed to the strong subband mixing between 1D-subbands in unstrained QWRS. The small increase in the e_2h_2-e_1h_1 subband separation energies (from 22 to 25 meV) was explained by the delicate balance between the variations of the QWR shape and the quantum confinement energies when the In content is increased. These results will have important implications for the realization of low threshold current, high gain QWR laser diodes.

4:10 PM, V8

Self-Ordered AlGaAs Vertical Quantum Wells: Formation Mechanisms, Structure and Optical Properties: GIORGIO BIASIOL[1]; E. Martinet[1]; A. Gustafsson[1]; H. Weman[1]; Y. Ducommun[1]; F. Reinhardt[1]; E. Kapon[1]; [1]Swiss Federal Institute of Technology-EPFL, Department of Physics, 1015 Lausanne Switzerland

Growth of AlGaAs alloys on V-grooved substrates by Organometallic Chemical Vapor Deposition (OMCVD) results in the formation of vertical quantum wells (VQWs), i.e., thin (<20 nm) vertical layers at the bottom of the grooves, with an Al concentration that is lower than that in the surrounding regions. In this work we will present a systematic study of the VQW segregation and confinement properties, and develop a model explaining their formation and characteristics. Cross-sectional transmission electron micrographs show that VQWs are composed of three distinct branches, forming on a set of (100) and {311}A nm-sized facets. Thanks to the self-ordering properties of OMCVD on V grooves, the size of the VQW remains constant during growth, and depends only on the growth conditions, i.e., it increases with increasing growth temperature T and decreasing nominal Al mole fraction x. We used cross-sectional atomic force microscopy in air to quantify the Al composition of the VQWS. Its dependence on x and T is formally identical to that of segregation models, and suggests a segregation energy Es=0.05±0.05eV. The amount of segregation is rather insensitive to T, and reaches a maximum of 0.15 for x=0.55. We have developed an analytical model that explains quantitatively this self-limiting growth, which results from an equilibrium between effects of growth rate anisotropy on the different planes composing the groove (that tend to sharpen it) and of adatom migration towards the bottom, due to curvature-related chemical potential differences (that tend to broaden it). During ternary growth, the stronger diffusion of Ga towards the bottom, with respect to Al, gives rise to an excess Ga concentration in this region, resulting in the VQW formation. However, this composition nonuniformity yields additional chemical potential gradients, related to the entropy of mixing, that reduce Ga surface diffusion. Comparison with experimental data confirms the predictions of this model, evidencing the importance of entropy-related diffusion. We measured the effects of T and x on quantum confinement by optical spectroscopy. The maximum confinement potential for electrons (140 meV) is achieved for T=650ϒC and x = 0.44, yielding a ~50meV subband separation. Lateral selective current injection into V-groove GaAs quantum wire (QWR) electroluminescent (EL) diodes was also demonstrated via the VQW forming at the QWR edges. The barrier lowering for electron and holes resulting from the VQW yields a reduced operating voltage and a dramatic spectral modification compared to photoluminescence: the EL is dominated from the QWR alone up to room temperature. These self-ordered VQWs should be useful for applications in normal incidence intersubband detectors in the 10-25 μm wavelength range and efficient and very low threshold current QWR laser diodes, respectively.

4:30 PM, V9

Optical Properties of V-Shaped AlGaAs/GaAs Quantum Wire Superlattices Grown By Flow Rate Modulation Epitaxy: WANG XUE-LUN[1]; Ogura Mutsuo[1]; Matsuhata Hirofumi[1]; [1]Electrotechnical Laboratory and Japan Science and Technology Corporation (JST), Electron Devices Division, 1-1-4 Umezono, Tsukuba, Ibaraki 305 Japan

Low dimensional quantum wire (QWR) and quantum dot superlattices (SLs) are expected to exhibit novel quantum effects which could not be achieved with single quantum structures due to the coherent interaction of quantum states. Recently, we succeeded in the fabrication of high-quality V-shaped AlGaAs/GaAs QWR-SL [1,2]. In this paper, we report several interesting optical properties observed from these V-shaped QWR-SL structures. The samples were grown on 4um pitch V-grooved GaAs (001) substrates by a newly developed selective growth technique, that is the use of Flow Rate Modulation Epitaxy (FME). The self-limiting behavior of FME growth on patterned substrate makes the formation of QWR-SLs with high size uniformity possible. The thickness of the GaAs wire layer was fixed at 4.5 nm, while that of the AlGaAs barrier layer was varied in the range of 4.5 to 18 nm. The QWR-SL structures showed very unique optical properties quite different from those observed in single QWR and two dimensional quantum well (QWL) structures. In 10 K photoluminescence (PL) spectra, several side peaks were observed on the two sides of the ground state main peak even with sufficiently low excitation power densities. These side peaks can not be attributed to the size fluctuation between different wires or impurity related emissions from their energy position and their optical behaviors. A more interesting result is observed in the low temperature PL excitation (PLE) spectra of a 20 period AlGaAs(13.5nm)/GaAs(4.5nm) QWR-SL sample. Instead of the sharp saw-tooth-shaped PLE spectra of a 4.5 nm thick single QWR, the AlGaAs(13.5nm)/GaAs(4.5nm) QWR-SL showed step-like PLE spectra. Moreover, there is almost no PLE single around the energy position of the ground state PL peak and the ground state PL emission mainly resulted from optical absorption by higher energy states and subsequent carrier relaxation. This result strongly suggests the coupling of quantum states of different QWRs though the electronic state is almost completely isolated by the thick AlGaAs barrier in this sample. Electromagnetic field (exciton polariton) induced quantum state coupling [3] which should be much more important in QWR structures than in QWL structures due to the large oscillator strength of QWR exciton is considered as a possible reason for this unique effect. Temperature dependent and time resolved results will also be presented at the conference. [1] X.L.Wang et al., J. Cryst. Growth 171 (1997) 341. [2] X.L.Wang et al., Superlattices and Microstructures, 22 (1977) 221. [3] D.S.Citrin, Phys. Rev. B49 (1994) 1943.

Thursday PM, June 25, 1998

Session W. IR Materials and Devices II

Room: 011
Location: Olsson Hall

Session Chairs: Parvez Uppal, Lockheed Martin-Sanders, Nashua, NY USA; Greg Charache, Lockheed Martin, Schnectady, NY

1:30 PM, W1+

Morphological Evolution of Liquid Phase Epitaxy $In_xGa_{1-x}As_ySb_{1-7}$ Layers on GaSb For Thermophotovoltaic Applications: V. BUCKLEN[1]; Y. C. Chen[1]; K. Rajan[1]; M. J. Freeman[2]; R. P. Cardines, Jr.[2]; [1]Rensselaer Polytechnic Institute, Department of Materials Science and Engineering, Troy, NY 12180-3590 USA; [2]Lockheed-Martin, Inc., Schenectady, NY 12301-1072 USA

Themophotovotaic generation of electricity is attracting renewed attention due to recent advances in low bandgap (0.5-0.7 eV III-V semiconductors. The use of these devices in various applications has been reviewed in a number of sources [1-3]. One potential low bandgap cell material is $In_xGa_{1-x}As_ySb_{1-y}$ grown lattice matched on GaSb substrates. These devices have been grown utilizing liquid phase epitaxy (LPE), molecular beam epitaxy (MBE), and organometallic vapor phase epitaxy (OMVPE). The electrical properties of these devices have recently equaled the performance level of lattice mismatched $In_xGa_{1-x}As$ [4]. There are a number of intrinsic advantages of the antimonide-based devices that warrant further investigation. The growth of smooth LPE layers appears to be very sensitive to alloy chemistry and the orientation of the GaSb substrate. This presentation addresses the strongly anisotropic nucleation process of epitaxial growth for this material system, resulting in highly facetted island growth. The role of interfacial surface energy and wetting in controlling the morphology of quaternary layers is discussed. [1] T.J. Coutts, J.P. Benner, Eds., The First NREL Conference on Thermophotovoltaic Generation of Electricity, AIP Conference Proceedings 321, American Institute of Physics, New York, 1994. [2] J.P. Benner, T.J. Coutts, D.S. Ginley, Eds., The Second NREL Conference on Thermophotovoltaic Generation of Electricity, AIP Conference Proceedings 358, American Institute of Physics, New York, 1995. [3] T.J. Coutts, M.W. Wanlass, J.S. Ward, and S. Johnson, "A Review of Recent Adances in Thermophotovoltaicx," 25th IEEE Photovoltaics Specialist Conference, 25 (1996). [4] T.J. Coutts, C.S. Allman, J.P. Benner, Eds., The Third NREL Conference on Thermophotovoltaic Generation of Electricity, AIP Conference Proceedings 401, American Institute of Physics, New York, 1996.

1:50 PM, W2+

Fabrication and Characterization of GaSb-Based Thermophotovoltaic Cells Using Zinc Diffusion from A Doped Spin-On-Glass Source: ISHAWA B. BHAT[1]; Dakshina Murthy[1]; Shivananda Shetty[1]; Collin Hitchcock[1]; Ron Gutmann[1]; Greg Charache[2]; Matt Freeman[2]; [1]Rensselaer Polytechnic Institute, ECSE Department, JEC 6032, Troy, NY 12180-3590 USA; [2]Lockheed Martin, Inc., Schenectady, New York 12301 USA

GaInSb material system is attractive for application in thermophotovoltaic (TPV) cells since its band gap can be tuned to match the radiation from the emitter. At present, most of the TPV cells are fabricated using epitaxially grown layers and hence are expensive. To reduce cost, Zn diffusion using elemental vapors in a semi-closed diffusion system is being pursued in several laboratories. In this paper, we present studies carried out on zinc diffusion into n-type GaSb and GaInSb substrates in an open-tube diffusion furnace using doped spin-on-glass. Zinc diffusion was carried out onto Te-doped n-type GaSb and GaInSb wafers in an open-tube diffusion furnace. The precursor was 1000A thick zinc doped spin-on-glass. Diffusion was carried out at a temperature range from 550 ϒC to 600 ϒC, for times from 1 to 10 hours. For a diffusion carried out at 600 ϒC for one hour onto GaSb, the junction depth was found to be 0.3mm, and the hole concentration near the surface was 5 x $10^{19}cm^{-3}$. The diffused layers were characterized by differential Hall measurements and secondary ion mass spectrometry. The profile is explained using the concentration-dependent diffusivity model. The quantum efficiency of the mesa-delineated TPV cells without any anti-reflection coating had a maximum value of 38%. Masked diffusions were also carried out by opening windows in a Si_3N_4 coated GaSb wafer. TPV cells fabricated on these structures had significantly better device properties. Detailed results on the diffusion process and device properties will be presented.

2:10 PM, W3

InGaAsSb Thermophotovoltanic Diode Physics Evaluation: G. W. CHARACHE[1]; P. F. Baldasaro[1]; L. R. Danielson[1]; D. M. DePoy[1]; C. A. Wang[2]; H. K. Choi[2]; D. Z. Garbuzov[2]; R. U. Martinelli[2]; [1]Lockheed-Martin, Inc., Schenectady, NY 12301-1072 USA; [2]Massachuetts Institute of Technology, Lincoln Laboratory, Lexington, MA 02173-1072 USA

The hotside operating temperatures for many projected thermophotovoltaic (TPV) conversion system applications are approximately 2000 F, which sets an upper limit on the TPV diode bandgap of 0.6 eV from efficiency and power density considerations. This bandgap requirement has necessitated the development of new diode material systems, never previously considered for energy generation application. To date, InGaAsSb quaternary diodes grown lattice-matched on GaSb substrates have achieved the highest performance. This report relates observed diode performance to basic diode properties such as minority carrier lifetime, diffusion length and mobility. This analysis has bounded potential diode performance improvements. Fig. I illustrates the comparison of the diffusion-limited dark current, the radiative limited dark current, a potential Auger-limited dark current and some experimental data for InGaAsSb devices. For the 0.52 eV InGaAsSb diodes used in this analysis the measured dark current is $2x10^{-5}$ A/cm^2, versus a potential Auger limit $1x10^{-5}$ A/cm^{-2}, a radiative limit of $2x10^{-6}$ A/cm^2 (no photon recycling), and an absolute thermodynamic limit of 1.4 x 10^{-7} A/cm^2. These dark currents are equivalent to open circuit voltage gains of 0.02 V (7%), 0.06 V (20%) and 0.14 V (45%), respectively. The Auger lifetime is proportional to the inverse of the doping level squared. Values of the proportionality constant (C-coefficient) have been determined both experimentally and theoretically by a number of techniques. Figure 2 presents a literature review of these results as a function of semiconductor bandgap. Similarly to the radiative lifetime coefficient data, there is a 1-2 order of magnitude-spread in these values and no data available for 0.5-0.6 eV material. However, if one interpolates the lowest C-coefficient for 0.5 eV material, this yields C ~2 x 10^{-28}cm^6/s. For $2x10^{17}$ cm^{-3} doped material, this yields a lifetime of ~125 ns, which is within a factor of 2 of dark current measurements.

2:30 PM, W4

Monolithic Interconnected Module (MIM) Thermophovoltaic Devices: BERNARD WERNSMAN[1]; Christopher S. Murray[1]; Marvin B. Clevenger[1]; [1]Westinghouse Electric Company, 814 Pittsburgh-McKeesport Blvd., West Mifflin, PA 15122 USA

A monolithic interconnected module (MIM) structure has been developed for thermophotovoltaic (TPV) applications. The MIM device consists of many individual InGaAs cells series-connected on a single semi-insulating InP substrate. An infrared back surface reflector, placed on the rear surface of the substrate, returns the unused portion of the TPV radiation output spectrum back to the radiator for recuperation, thereby providing high system efficiencies. The advantages of the MIM design include high output power density and voltage, simplified thermal management, and reduced dependence on minority carrier lifetimes. MIMs have been fabricated with a range of bandgaps from 0.74 eV to 0.55 eV. Parameteric measurements of the electrical performance of these devices under both a blackbody and white light source have been made. These results are compared to theoretical calculations using quantum yield and reflectance data experimentally measured. These results are reported.

2:50 PM, W5

InAs/InGaSb Type-II Superlattices for Mid-IR Photodetectors: MOHAMED AHOUJJA[1]; William C. Mitchel[1]; Gail J. Brown[1]; Frank Szmulowicz[1]; C. -H. Lin[2]; [1]AFRL/MLPO, WPAFB, BLDG 651, 3005 P ST STE 6, Dayton, OH 45433 USA; [2]Space Vacuum Epitaxy Center, Sience and Research One, University of Houston, Houston, TX 77204 USA

InAs/InGaSb type-II strained layer superlattices (SLSs) operating at 10 microns were grown and characterized. An 8x8 envelope function approximation (EFA) model was developed to obtain the structural parameters, layer thickness and indium composition, for optimum infrared absorption in a superlattice with an energy bandgap of 120 meV. The SLSs were grown on a p-type (001) GaSb substrate in a Riber 32 molecular beam epitaxy system and were composed of

100 to 150 periods of unintentially doped 43.6 Angstroms InAs and 17.2 Angstroms $In_{0.23}Ga_{0.77}Sb$ layers. In order to investigate and reduce the background carrier concentrations, SLSs with different substrate temperatures were compared before and after annealing. Structural, electrical, and optical characteristics were measured to assess material quality. Structural characterization was performed using double-crystal x-ray diffraction (DXRD) measurements. The electrical properties were determined using standard Hall measurements as well as B-field dependent Hall measurements. Optical characterization was obtained from photoresponse spectra using a BIO-RAD Fourier Transform spectrometer. The SL period of the samples studied, determined by DXRD, was on the average 59.6 Angstroms, versus a designed period of 60.8 Angstroms. The measured SL periods ranged from 58.72 to 61.18 Angstroms, a variation of less than one monolayer. The average measured cut-off energy, where the photoresponse intensity drops to 50%, was 116 +/- 6 meV. This demonstrated good agreement with the designed superlattice bandgap. The intensity of the measured mid-infrared photoresponse was found to improve by an order of magnitude for the superlattice grown at lower substrate temperature (390 ϒC) and then annealed at 520 ϒC for 10 minutes. However, the photoresponse of the sample grown at higher substrate temperature (450 ϒC) remained the same before and after annealing. The x-ray diffraction spectra were very similar for both samples before and after annealing. The SL bandedge remained sharp and only shifted by about 5 meV toward higher energy after annealing. For all the superlattices studied the low temperature (T < 25 K) carrier concentrations were around $1x10^{12}$ cm^{-2}. The sheet carrier concentration in the sample grown at lower substrate temperature remained nearly the same before and after annealing. The in-plane mobility decreased slightly after annealing. This slightly lower mobility is probably a factor in boosting the sample=s resistance, and hence photoresponse intensity. However, the differences are not large enough to account for a factor of eight increase in the photodetected signal. The mobility spectrum method was used to identify the different conducting layer in the SLSs. A clear separation of electrons and holes in their respective SL layers was observed. In general, electrical conduction was dominated by the SL layers at lower temperatures and by the GaSb substrate layer at higher temperatures.

3:10 PM Break

3:30 PM, W6+

Microstructural Evaluation of Sb-Based Buffer Layer Systems for TPV Applications: ERIC CHEN[1]; Parvez Uppal[1]; John S. Ahern[1]; Kirby Nichols[1]; David C. Paine[1]; [1]Brown University, Division of Engineering, Providence, RI 02912 USA

The implementation of GaAs substrates for the fabrication of InAs-based IR detectors has been achieved through the use of a novel buffer layer system. Typical buffer layer schemes (e.g. InGaAs) modify the Group III content to effect a change in lattice parameter. In this presentation we report on a study of Sb-adjusted ternary (GaAsSb) and quarternary (AlGaAsSb) alloy buffer layer structures that have been used in the fabrication of 2.2 μm power converter structures. A multilayer grading scheme was used in which the Sb content of $Al_{0.5}Ga_{0.5}As_{1-x}Sb_x$ and $GaAs_{1-x}Sb_x$ is successively increased in a ten step series of 100 nm thick layers. We have shown, using plan view and cross-sectional TEM, that this approach can reduce the threading defect density to below the detectability of TEM ($10^5 cm^{-2}$) and preserve growth surface planarity. Microstructure, defect density and device performance in the Sb-based buffer layers is compared to equipvalent devices fabricated using InP substrates.

3:50 PM, W7+

Spectral Ellipsometry Investigation of n- And p-Doped $In_{0.66}Ga_{0.34}As$ Grown on InP (001): Todd Holden[1]; FRED H. POLLAK[1]; J. L. Freeouf[2]; Greg Charache[3]; James L. Egley[3]; Paul R. Sharps[4]; Michael L. Timmons[4]; [1]Brooklyn College of the City University of New York, Physics Department and New York State Center for Advanced Technology in Ultrafast Photonic Materials and Applications, Brooklyn, NY 11210 USA; [2]Inudies, Inc., Katonah, NY 10536 USA; [3]Lockheed Martin, Schenectady, NY 12301 USA; [4]Research Triangle Institute, Research Triangle Park, NC 27709 USA

Spectral ellipsometry at 300 K, in the range 0.3-5.4 eV, has been used to determine the complex optical constants for a series of n-(5.7×10^{17} cm^{-3} < n < 5.5×10^{19} cm^{-3}) and p-(6.5×10^{17} cm^{-3} < p < 5.0×10^{19} cm^{-3}) doped relaxed $In_xGa_{1-x}As$ (x = 0.66) grown on InP (001) by molecular beam epitaxy. These materials are significant for thermal photovoltaic applications. The optical functions of lightly doped samples near the fundamental bandgap were fit using a square root line-shape yielding a bandgap of 0.61 eV, which corresponds to an In composition of 66%. The more heavily doped samples exhibited Burstein-Moss shifts of the fundament al absorption edge, particularly the n-type samples. Blue shifts of up to 0.5 eV were observed. For the n-doped samples, the band gap variation can be explained by band filling near the Γ point, including nonparabolic effects, except for the highest n-doped sample (5.5×10^{19} cm^{-3}), which showed a smaller than expected change. This observation may be due to the transfer of electrons from the G minimum to the L valley. The Burstein-Moss shift makes it possible to accurately determinate the doping from the measured fundamental absorption edge, especially for n-doped samples (< $5.5x10^{19}$ cm^{-3}). For all samples, we observed the E_1, $E_1+\Delta_1$ doublet (spin orbit split transitions along the < 111> directions of the Brillouin zone) and the E_2 transition. The values of the E_1, $E_1+\Delta_1$ energies are in good agreement with the quadratic interpolation of the data of Pickering et al. [APL 60, 2412 (1992)] for other alloy compositions of relaxed material (0 < x < 0.53 and x = 1.0). A detailed lineshape fit to the optical functions for the entire range of data has been performed for the lightly doped material.

4:10 PM, W8+

Structure and Properties of Highly Strained InAsSb/InAs Multi-Quantum Wells: SCOTT C. THEIRING[1]; Manoj R. Pillai[1]; Scott A. Barnett[1]; BRUCE W. WESSELS[1]; [1]Northwestern University, Materials Science and Engineering, 2225 N. Campus Dr., Evanston, IL 60208 USA

Highly-strained InAsxSb1-x/InAs multi-quantum wells with alloy compositions ranging from $0.40 \leq x \leq 0.95$ have been grown for long wavelength applications. The multi-quantum well structures were prepared by metalorganic vapor phase epitaxy (MOVPE), and deposited on InAs (111)A substrates. The (111)-oriented superlattices were grown in order to test theoretical predictions on the dependence of band structure on orientation. The structural perfection was measured by double crystal x-ray diffraction, and high quality multi-layer structures were obtained for well concentrations as high as x = 0.54. Computer simulations of the x-ray patterns were used to quantify the compositional broadening at the interfaces, the interface roughness, and residual strain. Compositional broadening was observed and ascribed to surface segregation of the antimony during deposition. The degree of antimony segregation was determined, and for arsenic concentrations of $x \oplus 0.80$, it was nearly independent of composition with ~0.9 ML of segregated antimony being observed. For the structures with x < 0.80, the simulations indicated that the layers were partially relaxed with respect to the substrate, and for these compositions the degree of antimony segregation was found to decrease with increasing antimony content. This is consistent with segregation being enhanced by the lattice misfit strain between antimony-containing layers and the pure InAs substrate and barrier layers. The roughness of the interfaces between subsequent layers was calculated by simulation to be between 3.5 and 8Å for films with x = 0.54 and x = 0.89 respectively. Like the degree of segregation, the interface roughness was seen to decrease with increasing antimony concentration down to the minimum arsenic content of x = 0.54. The optical response of the photoconductivity of the structures was measured by Fourier-transform infrared spectroscopy at temperatures from 77 K to 295 K and compared to the calculated band structure.

4:30 PM, W9
Late News

4:50 PM, W10
Late News

Thursday PM, June 25, 1998

Session X. Growth and Characterization of Nitrides

Room: 120
Location: Olsson Hall

Session Chairs: Russ Dupuis, University of Austin, Microelectronics Research Center, Austin, TX 78712-1100 USA; Supratik Guha, IBM Research, Yorktown Heights, NY 10598

1:30 PM, X1

Gas-Phase Reactions During MOCVD Growth of AlGaN: JUNG HAN[1]; Jeff J. Figiel[1]; Robert M. Biefeld[1]; Mary H. Crawford[1]; [1]Sandia National Laboratories, Dept. 1126, MS-0601, P. O. Box 5800, Albuquerque, NM 87185-0601 USA

Very high ammonia (NH_3) partial pressures are often employed in the MOCVD growth of GaN (to compensate the surface loss of nitrogen) which tends to encourage the formation of the Lewis acid-base complexes (adducts) between NH_3 and metal-organic molecules (such as trimethylaluminum, TMA, and trimethylgallium, TMG) in the gas phase. The gas-phase pre-reactions complicates the growth chemistry and could lead to the introduction of hydrocarbon impurities. In many cases such gas-phase pre-reactions could also cause the depletion of reactants when adducts of large molecules with low vapor pressures are not efficiently transported to the growth surface. The gas-phase reactions between NH_3 and two metal-organic precursors, TMA for the growth of AlGaN and biscyclopentadienyl-magnesium (Cp_2Mg) for p-type doping will be reported in this work. It has been reported (Ludowise et al., JEM, 1996) that the gas-phase reaction between TMA and NH_3 leads to a reduction of growth rate. We will report the results of an in-situ monitoring of the growth rate variations, due to the TMA: NH_3 reaction, over a wide range of gas compositions. The formation of the (TMA:NH_3) adduct not only depletes TMA from gas stream but also indirectly inhibits the incorporation of TMG. We observed that the incorporation of TMG could be reduced by more than 60%, probably due to either the scavenging effect of TMG by the TMA:NH_3 adduct in the gas phase, or an adduct-related site blocking on the surface. After we established a correlation between the degree of gas-phase reactions (between TMA and NH_3) and the gas partial pressures through the in-situ reflectance monitor, we then investigated the incorporation of Mg as a function of NH_3 partial pressures over a similar range. We note that the gas-phase reaction during Mg-doping of GaN in MOCVD has not received much attention (except a recent paper by Haffouz et al., MRS Internet Journal, 1997) even though it is indirectly implied from the very wide range of Mg flow rates (doping efficiency) reported in the literature. We observed (from SIMS measurements) that the efficiency of Mg incorporation is reduced from nearly 100% to 0.01% as the NH_3 pressure is increased from 20 to 80 Torr. The implication is that the very high Mg to Ga flow ratios (up to 300) employed by other works serve to compensate the gas-phase depletion of Cp_2Mg. In our case a Mg to Ga molar flow ratio of 1/200 yielded a Mg concentration of approximately $1.5x10^{20}$ cm^{-3} (around 1/200 of the atomic concentration of Ga) which in turn results in a free hole concentration of $1.2x10^{18}$ cm^{-3}.

1:50 PM, X2

Improvements in the Quality of AlGaN, InGaN, and GaN Grown on Lithium Gallate Via Plasma Assisted Molecular Beam Epitaxy: W. A. DOOLITTLE[1]; S. Kang[1]; T. J. Kropewnicki[1]; Y. Hsu[2]; T. S. Kuan[2]; S. Stock[1]; P. A. Kohl[1]; A. S. Brown[1]; [1]Georgia Institute of Technology, School of Electrical and Computer Engineering, 777 Atlantic Dr., Atlanta, GA 30332-0250 USA; [2]University at Albany, SUNY, Department of Physics, 1400 Washington Ave., Albany, NY 12222 USA

Lithium gallate (LGO) is the closest known lattice matched material to GaN. Recent advances in the understanding of this material have lead to dramatic improvements in nitride film quality grown on this novel substrate. In particular, the structural and optical quality of very thin nitride films grown by molecular beam epitaxy on this substrate are comparable to those grown much thicker on sapphire by MOCVD at substantially higher temperatures. However, many challenges exist for growing GaN on LGO. We will discuss the growth of GaN, AlGaN, and InGaN on LGO via Plasma Assisted MBE with emphasis on the improvement in the crystal quality to such a point as to allow removal of the substrate and placement onto foreign host substrates. Growth conditions, pre-growth chemical and annealing conditions, and group III/V optimization of growth conditions will be presented. Films less than 0.3 microns thick have resulted in 145 arc-sec FWHM X-Ray rocking curves, while thicker films have resulted in 85 arc-sec FWHM. X-Ray FWHM verses growth temperature indicates a broad minimum around 600 degrees C (thermocouple temperature). This temperature is 400 to 500 degrees lower that typical MOCVD grown material of comparable quality. TEM and X-Ray diffraction results indicate an strong epitaxial orientation relationship of nitride films to the substrate with very little mosaic structure. Dark field, cross-sectional TEM indicates a dislocation density of the order of $7x10^8$ to $3x10^9$ cm^{-2} which is comparable to MOCVD films on sapphire at higher temperatures. Cross sectional TEM results will be discussed. Very strong UV photoluminescence is observed on GaN films grown at moderately low temperatures with exciton features clearly visible at 78 degrees kelvin. Yellow luminescence observed in photoluminescence spectra was found to result from fluorescence of the LGO substrate, and not from the GaN film. The electrical properties of nitride films grown on LGO are currently poorer than films on other substrates and have typically been plagued with high residual doping and low mobilities. However, we obtained highly resistive material on undoped GaN films. Improvements, relative to previous work on LGO, in the electron mobility of doped films have been obtained with bulk GaN mobilities as high as 100 cm^2 /V-Sec for a silicon doped ($7.8x10^{17}$ cm^{-3}) sample. PL, TEM, SIMS, AFM, hall mobility and X-ray diffraction results will be discussed for various undoped and doped nitride films.

2:10 PM, X3

Study of Mg Diffusion During Metalorganic Chemical Vapor Deposition (MOCVD) Of GaN And AlGaN: YING-LAN CHANG[1]; Mike Ludowise[1]; Mike Ludowise[1]; Dale Lefforge[1]; Bill Perez[1]; [1]Hewlett-Packard Company, Solid-State Technology Laboratory/Hewlett-Packard Laboratories, 3500 Deer Creek Road, MS 26L, Palo Alto, CA 94304 USA

GaN-based nitride semiconductors have gained increasing importance in recent years in luminescent and electronic device applications. Although p-type GaN has been obtained with Mg doping, the diffusion behavior of Mg during the MOCVD growth is not well understood. Secondary ion mass spectrometry (SIMS) has been widely used for the characterization of dopant profiles. However, the presence of non-planar, V-shaped defects, found commonly in InGaN/GaN heterostructures, cause significant distortion of the Mg profiles measured by SIMS. Determination of junction position then becomes difficult. In this work, we study the behaviors of Mg in GaN and AlGaN layers using otherwise undoped GaN test structures containing three Mg-dopant spikes. These simplified structures enable accurate SIMS profiling by avoiding the formation of non-planar V-shaped defects, as confirmed by atomic force microscopy measurements. SIMS analysis is performed using a Cameca IMS-4f instrument with a Cs^+ primary ion source. The impact energy is 1.5KeV. Mg ion-implanted GaN and AlGaN samples serve as calibration standards. The Mg profiles in GaN show an abruptness of about one decade per 30 nm. The doping level saturates at about $4x10^{19}$ cm^{-3}. No significant difference is observed among the three Mg spikes, indicating negligible Mg diffusion during the two hour MOCVD growth. A longer Mg tail extending towards the surface indicates some reactor memory effect. Additionally, we compare GaN:Mg, and GaN:Mg/AlGaN structures to investigate the effects of Al on the behavior of Mg. We do not observe any significant change of Mg profiles due to the presence of adjacent AlGaN layer. We will present details of the materials growth and SIMS profiles, which support the conclusion that Mg diffusion is negligible in MOCVD grown GaN and AlGaN structures. Only minor reactor memory effects account for the small deviations from ideal profiles. The distortion of SIMS profiles acquired from InGaN/GaN heterostructures due to the formation of non-planar V-shaped defects will also be discussed.

2:30 PM, X4

Boron-Containing Nitrides Grown by Molecular Beam Epitaxy: C. C. WAMSLEY[1]; V. K. Gupta[1]; M. W. Koch[1]; G. W. Wicks[1]; [1]The Institute of Optics, University of Rochester, Rochester, NY 14627 USA

GaN and AlGaN materials are improving rapidly, but progress is still hampered by the inability to lattice match a commercial substrate. The incorporation

of boron into the nitride materials could potentially alleviate this problem, as BAlGaN materials are theoretically capable of lattice matching SiC. The small lattice constant and large bandgap energy of these boron containing nitride alloys may also prove useful in the engineering of piezo-electric structures and strained quantum wells. Research is presented on the growth of boron-containing nitrides by molecular beam epitaxy. The boron source is a high temperature effusion cell equipped with a tungsten crucible and pyrolytic graphite liner. The boron cell can achieve temperatures up to 2000° C, which corresponds to a BN growth rate of 150 Å/hr and BGaN compositions greater than 12% (boron nitride mole fraction). Growth was performed on nitrided (0001) plane sapphire at T_s = 850° C. Before commencing growth, a thin 200 Å AlN buffer is deposited at T_s = 850° C. Reactive nitrogen is generated by cracking ammonia on the substrate surface. Ammonia is injected into the machine at room temperature using a valved injector. Photoluminescence (PL) measurements of $B_xGa_{1-x}N$ (x<0.03) layers show a monotonic increase in the bandgap energy and reduced PL intensity with increasing boron composition. Although the MBE hardware is capable of growing alloys greater than 12% boron, room temperature PL has been observed in alloys up to only 3%. Post growth rapid thermal annealing at 950° C has shown to improve PL intensities by ~10X in the higher boron containing samples. A reduced BGaN growth rate, due possibly to radiant heating of the substrate by the boron source, has also been observed. Reflection high energy electron diffraction (RHEED) along with X-ray diffraction reveal that low boron (small x) containing alloys grow single crystal in the wurtzite structure on (0001) sapphire substrates. RHEED and Fourier Transform Infrared transmission measurements suggest that high boron (large x) containing layers, including BN, grow as polycrystalline films in a hexagonal phase. Amorphous BN may also be present. Data will also be presented on the electrical characteristics of these boron-containing nitrides.

2:50 PM, X5+

As and P Incorporation in GaN Grown by Gas Source Molecular Beam Epitaxy: Y. ZHAO[1]; Y. Zheng[1]; F. Deng[1]; S. S. Lau[1]; C. W. Tu[1]; I. Bae[2]; T. Seong[2]; [1]Univ. of California, San Diego, Electrical and Computer Engineering, 9500 Gilman Dr., La Jolla, CA 92093 USA; [2]Kwang-Ju Institute of Science and Technology, 572 Sangam-dong, Kwangsan-Ku, Kwang-Ju 605-712 South Korea

N-rich GaNAs and GaNP alloys are currently attracting increasing attention because of their potential applications in wide-bandgap devices. Theoretical calculations predict a rapid bandgap shrinkage would occur as GaN is alloyed with a small amount of As or P. This unique property may provide another possibility for bandgap engineering in the nitrides. In this paper, we report As and P incorporation into GaN using cracked AsH_3 and PH_3. The nitrogen source is an Applied Oxford RF radical beam source. GaNAs and GaNP are grown on MOCVD-grown (0001) GaN/sapphire substrates by gas-source molecular beam eptiaxy (GSMBE) and characterized by atomic force microscopy (AFM), Rutherford backscattering (RBS), energy disperse X-ray (EDX) analysis, transmission electron microscopy (TEM), X-ray diffraction, and room-temperature absorption measurement. When the growth temperatures is above 730 °C, little As or P is found in the epilayers due to desorption of As or P from the growing surface. Study of morphology by AFM shows that the presence of P during growth roughens the grown surface but As smooths the surface as a surfactant. We believe that this difference of As and P is related to their different atomic size and chemical bonds. Namely, the large size of As atoms makes As more difficult to be incorporated into GaN. To suppress desorption, the growth temperature is lowered and a large As or P beam flux is used. As or P is found by EDX in epilayers grown at 500 °C. RBS spectrum shows about 1% As incorporation into a GaN epilayer grown at this temperature. The transmission electron diffraction (TED) pattern, however, suggests that this GaNAs film is polycrystalline. The formation of GaNAs alloy is also confirmed by our room-temperature optical absorption spectrum which shows an optical absorption edge at 2.36 ± 0.02 eV with a large bandtail (bandtail parameter E_0 = 0.04 eV). Compared to GaNAs growth, excess P is deposited on the sample surface under identical growth conditions. No evidence of GaNP alloy is found by X-ray rocking curve and ϑ-2ϑ scan, but the latter clearly shows a phase separation between wurtzite GaN and GaP. In summary, we found that low-temperature growth reduces the desorption of As or P and therefore increases their incorporation into the growing films. At the growth temperature of 500 °C, we obtained a GaNAs polycrystalline film which shows a large bandgap shrinkage. Though P is found easier to be incorporated, a large amount of P leads to a multiphase alloy.

3:10 PM Break

3:30 PM, X6

Polarity and Structure of Wurtzite GaN Surfaces: A. R. SMITH[1]; R. M. Feenstra[1]; D. W. Greve[2]; M.-S. Shin[3]; M. Skowronski[3]; J. Neugebauer[4]; J. Northrup[5]; [1]Carnegie Mellon University, Department of Physics, 5000 Forbes Ave., Pittsburgh, PA 15213 USA; [2]Carnegie Mellon University, Department of Electrical and Computer Engineering, 5000 Forbes Ave., Pittsburgh, PA 15213 USA; [3]Carnegie Mellon University, Department of Materials Science and Engineering, 5000 Forbes Avs., Pittsburgh, PA 15213 USA; [4]Fritz-Haber-Institut der MPG, Faradayweg 4-6, D-14195, Berlin, Germany; [5]Xerox Palo Alto Research Center, 3333 Coyote Hill Road, Palo Alto, CA 94304 USA

Using a combination of scanning tunneling microscopy (STM) measurements and first-principles theoretical computations, we have identified the polarity and geometric structure of the surfaces of wurtzite GaN obtained during growth by molecular beam epitaxy (MBE). Many of the surfaces are found to contain excess gallium compared to a bulk-terminated surface, leading to a variety of novel structures. Two classes of surface reconstructions are obtained, one associated with the (0001) surface (Ga-face), and the other with the (0,0,0,-1) surface (N-face). The two faces are grown in our MBE system under nearly identical growth conditions, with the N-face produced by nucleating the GaN directly on a nitrided sapphire (0001) substrate and the Ga-face produced by homoepitaxial growth on an MOCVD-grown GaN/sapphire substrate. For the N-face we observe 1x1, 3x3, 6x6, and c(6x12) reconstructions, while for the Ga-face we find 2x2, 5x5, 6x4, and "1x1". The absolute polarity identification is determined primarily through first-principles theoretical total energy calculations, where it is found that a lowest-energy 1x1 structure exists only for the N-face. A polarity-selective wet chemical etching experiment confirms the identification, in agreement with the results of Seelmann-Eggebert et al.[1] From the theoretical calculations, it is found that the N-face 1x1 consists of a single monolayer of Ga atoms sitting directly atop the N atoms of the last GaN bilayer. Both theory and scanning tunneling spectroscopy (STS) measurements reveal that this surface is metallic. The 3x3 and other higher order reconstructions are formed by depositing sub-monolayer quantities of Ga atoms onto the 1x1; the additional adatoms occupy sites on top of the Ga monolayer, relieving some of the stress in this monolayer. The Ga-face "1x1" surface is found to consist of at least 2 ML of Ga on top of the Ga-terminated bilayer, as revealed by STM and Auger electron spectroscopy; STS confirms its metallic nature. Electron diffraction on this surface at temperatures below 350 ϒC reveals satellite peaks surrounding the integral-order peaks. From the detailed intensity distribution and temperature-dependence of the satellites, we infer that the surface structure is best characterized as a discommensuration-fluid phase, consisting of a compressed bilayer of Ga on top of the Ga-terminated bilayer, with the Ga bilayer having a slightly buckled arrangement due to its misfit with the underlying GaN. At room temperature or above, this Ga bilayer is in a dynamic, fluid-like state. Removing Ga atoms from the "1x1" yields the 2x2 and other higher order reconstructions on this face. Theory suggests that N adatoms may be involved in at least some of these structures, particularly 2x2. [1] M. Seelmann-Eggebert, J. L. Weyher, H. Obloh, H. Zimmermann, A. Rar, and S. Porowski, Appl. Phys. Lett. 71, 2635 (1997). This work was supported by the Office of Naval Research under contractN00014-96-1-0214.

3:50 PM, X7

Single Temperature Process for Nucleation Of Group III-Nitrides On SiC, Sapphire And Si: J. A. Smart[1]; A. T. Schremer[1]; J. R. SHEALY[1]; [1]Cornell University, School of Electrical Engineering, Ithaca, NY USA

Using an appropriate surface pre-treatment and by the introduction of low aluminum mole fractions in AlGaN, a single temperature process produces device quality GaN-based materials with smooth growth surfaces. The process has been modified for successful growth of AlGaN on sapphire, SiC and Si substrates, where the conditions for successful nucleation are quite different. The Flow Modulation Epitaxial technique is used in a low pressure Organometallic Vapor Phase Epitaxial growth apparatus with hydrogen and ammonia mixtures as the carrier gas. The nucleation/growth temperature for sapphire and SiC substrates was chosen to be 1040ϒC and 1010ϒC, respectively, while experiments on Si produced little or no nitride growth at these elevated temperatures. By reducing the temperature to 800ϒC, smooth AlGaN films on Si result with strong photoluminescence. The V/III ratio was modulated through the nucleation process from low values up to 1800 during growth. The group III flux (triethylgallium and trimethylaluminum in this case) is modulated in roughly a 25 % duty cycle with a period of 10 seconds throughout the entire growth. The alloy

composition of the nucleation layer required some optimization for each substrate. For SiC (both 4H and 6H), compositions from no aluminum to up to 35 % resulted in featureless growth surfaces as long as the layer thickness exceeded roughly 1000 Å where substrate surface scratches disappear. However, only aluminum mole fractions near 6 % within in this range allowed thick GaN (up to 3 μm) to be grown without cracks forming. For sapphire, the AlGaN nucleation layer only grows smooth for aluminum mole fractions exceeding 12 %. The surface texture on sapphire was slightly poorer than the SiC, but the films remain optically smooth. Finally, for (111) Si substrates, the AlGaN nucleation layer required roughly 30 % aluminum mole fraction to produce smooth growth surfaces. The deep yellow and green band emission was only observed on the Si substrates, whereas only UV emission was observed on the SiC and sapphire. The SiC substrates consistently produced the strongest and narrowest photoluminescence band edge peaks which range from 280 to 365 nm depending on the alloy composition. Photoluminescence line widths (FWHM at 300 K) on GaN films grown on the AlGaN buffers are as low as 30 meV for SiC, and in the range of 50 to 60 meV on the sapphire, and 100 meV on the Si substrates. For sapphire and SiC substrates the transport properties parallel to the growth surface on the GaN films were evaluated in the following manner. An AlGaN layer is grown on the GaN to introduce a small amount of piezoelectric charge near the sample surface. Note that undoped GaN films have low carrier concentrations ($<10^{14}$ cm^{-3}) making the preparation of Hall samples difficult. The resulting two dimensional electron gas is designed to have a low sheet density. In the low sheet density limit, the Hall mobility data on these structures is representative of the transport properties in the bulk GaN film at its surface away from the defective buffer. The 300 K mobilities observed on 1.5 μm thick GaN films were 550 and 850 cm^2/volt.sec on sapphire and semi-insulating 4H-SiC, respectively, for electron sheet densities on the order of 10^{12} cm^{-2}. This indicates that the defect densities are lower or decreasing faster with growth on the SiC substrates using these AlGaN nucleation layers. This work has been partially supported by DARPA and ONR.

4:10 PM, X8

The Impact of Nitridation and Nucleation Layer Process Conditions on Morphology And Electron Transport in GaN Epitaxial Films: ALMA ESTES WICKENDEN[1]; Daniel D. Koleske[1]; Richard L. Henry[1]; Robert J. Gorman[1]; James C. Culbertson[1]; Mark E. Twigg[1]; Jaime A. Freitas[1]; [1]Naval Research Laboratory, Electronics Science & Technology, Code 6800, 4555 Overlook Avenue, S.E., Washington, DC. 20375-5320 USA

The growth of high mobility, controllably doped GaN and highly resistive unintentionally-doped GaN films is required for microwave and power electronic devices in this wide bandgap materials system. Several groups have demonstrated the need for optimization of both the ammonia pretreatment of the substrate (nitridation) and the nucleation layer (NL) growth to reduce background carrier concentration and improve mobility in MOCVD growth of GaN on sapphire. However, neither the physical effects of the growth process variables on the film structure nor the relationship of the morphological structure of the GaN film to its transport properties are fully understood. The question presented to the grower is: What does an optimized NL look like, and how is it achieved? To address this question, a systematic study of the relationship between growth process parameters and the resultant properties of low temperature GaN NL's and high temperature epitaxial GaN films has been performed, during GaN process development in a close-spaced showerhead reactor. Using atomic force microscopy (AFM) and cross-sectional transmission electron microscopy (XTEM), we have determined the influence of the temperature at which ammonia is introduced to the process and of the ammonia total dose (temperature, exposure time and flux) on the subsequent initiation of NL growth, its grain structure, and the alignment of its crystallites. The dislocation structure and the transport properties in subsequently grown epitaxial GaN films have been investigated as a function of MOCVD process conditions, using XTEM and Hall analysis, respectively. The use of large deviations from normal NH_3/TMG ratios, toward either Ga- or N- rich conditions, has been demonstrated as necessary to create a NL which is able to anneal in better registry and present a more optimized template to the high temperature film growth. Five-fold increases in mobility and ten-fold decreases in electron concentration have been demonstrated in Si-doped GaN films as a function of nitridation and nucleation layer process optimization. In addition, highly resistive unintentionally-doped GaN films with breakdown voltages in excess of 1000V have been grown, which have exhibited free exciton emission in low temperature photoluminescence (PL). The optical and transport characteristics of GaN films will be related to structural differences caused by varying specific process parameters.

4:30 PM, X9+

Selective Laser Processing for Lift-Off of GaN Thin Films from Sapphire Substrates: WILLIAM S. WONG[1]; Joachim Krueger[2]; Yonah Cho[3]; Eicke R. Weber[4]; Timothy Sands[5]; Nathan W. Cheung[6]; [1]University of California, Department of Materials Science and Mineral Engineering, 211-181 Cory Hall, #1772, Berkeley, CA 94720-1772 USA; [2]Lawrence Berkeley National Laboratory , Materials Science Division, Bldg. 2-200, 1 Cyclotron Road, Berkeley, CA 94720 USA; [3]University of California, Department of Materials Science and Mineral Engineering, 227-161M Cory Hall,#1772, Berkeley, CA 94720-1772 USA; [4]University of California, Department of Materials Science and Mineral Engineering, 587 Evans Hall, Berkeley, CA 94720 USA; [5]University of California, Department of Materials Science and Mineral Engineering, 559 Evans Hall, Berkeley, CA 94720-1760 USA; [6]University of California, Department of Electrical Engineering and Computer Science, 513 Cory Hall, Berkeley, CA 94720 USA

Advances in the growth and processing of GaN thin films have allowed rapid development of GaN based light-emitting diodes and lasers. In spite of this swift progress, the symmetry of the GaN crystal structure, combined with the high GaN growth temperatures prevents deposition of high-quality material directly onto common semiconductor substrates such as GaAs, InP or Si. This restriction impedes the direct integration of GaN with existing electronic and optoelectronic semiconductor technologies. The most commonly used growth substrate, sapphire, still imposes constraints on GaN based devices due to its relatively low thermal conductivity for high power electronic applications and difficulty in cleaving smooth mirror facets to form laser cavities. We have investigated and will demonstrate the effectiveness of uv pulsed-laser processing to separate GaN thin films from sapphire substrates. The nanosecond-scale pulse lengths and the materials selectivity afforded by the uv wavelength are advantages over conventional wet etch lift-off techniques. GaN thin films on sapphire substrates were successfully separated from the sapphire to create free-standing GaN membranes using a single 38 ns KrF excimer laser pulse directed through the transparent sapphire substrate.[1] The absorption of the 248 nm radiation by the GaN at the interface induces rapid thermal decomposition of the interfacial layer, yielding metallic Ga and N_2 gas, thus allowing the GaN film to separate from the substrate. The laser lift-off process was also used to successfully transfer GaN from sapphire substrates onto Si substrates. In this talk, characterization of the lifted off GaN films by scanning electron microscopy, atomic force microscopy (AFM), x-ray diffraction and photoluminescence (PL) will be presented. We will show that the laser lift-off process does not degrade the structural and optical qualities of the GaN films. Surface roughness of the exposed GaN interface was measured to be ~20 nm (rms) by AFM. Low-temperature (4 K) PL spectra of the free-standing GaN films showed a shift of the donor bound exciton peak from 3.477 eV to 3.466 eV suggesting stress relief of the GaN film after lift-off from the sapphire.[2] It will also be shown that parallel prismatic cleavage facets can be formed by mechanically stressing the free-standing GaN membranes. [1] W.S. Wong, T. Sands and N.W. Cheung, Appl. Phys. Lett 72, 599 (1998). [2] C. Kisielowski, J. Krüger, S. Ruvimov, T. Suski, J.W. Ager III, E. Jones, Z. Liliental-Weber, M. Rubin, E.R. Weber, M.D. Bremser, R.F. Davis, Phys. Rev. BII 52, 17745 (1996).

Thursday PM, June 25, 1998

Session Y. Ordering

Room: E303
Location: Thronton Hall

Session Chairs: Henryk Temkin, Texas Tech University, Electrical Engineering, Lubbock, TX 79409 USA; Jacek Furdyna, University of Notre Dame, Dept. of Physics, Notre Dame, IN 46566 USA

1:30 PM, Y1

Observation of CuPt-A Atomic Ordering in MBE Grown $Al_xIn_{1-x}As$: T. SUZUKI[1]; T. Ichihashi[2]; T. Nakayama[3]; [1]NEC Corporation, Opto-Electronics & High-Frequency Device Research Laboratories, 34 Miyukigaoka, Tsukuba, Ibaraki, 305-8501 Japan; [2]NEC Corporation, Fundamental Research Laboratories, 34 Miyukigaoka, Tsukuba, Ibaraki, 305-8501 Japan; [3]NEC Corporation, Kansai Electronics Research Laboratories, 2-9-1 Seiran, Otsu, Shiga, 520-0833 Japan

CuPt-B atomic ordering is most commonly observed in a wide range of III-V alloys[1]. In addition to this type of ordering, TP-A type ordering was found in arsenides ($Al_{0.5}In_{0.5}As$ and $Ga_{0.5}In_{0.5}As$) grown under the (2x3) surface reconstruction[2], while CuPt-A was observed only in phosphides ($Al_{0.5}In_{0.5}P$ and $Ga_{0.5}In_{0.5}P$)[3]. This paper reports, for the first time, observations of CuPt-A ordering in MBE grown $Al_xIn_{1-x}As$ for which only CuPt-B and TP-A types have been reported heretofore. $Al_xIn_{1-x}As$ layers were grown on $Ga_{0.5}In_{0.5}As$ with InP(001) substrate using solid-source MBE. CuPt-A was found to be formed in Al-rich $Al_xIn_{1-x}As$ such as $A_{l0.9}In_{0.1}As$ and $Al_{08}In_{0.2}As$. RHEED patterns during the growths were (1x2). Thus the previous conjecture[3] that (1x2) surface reconstruction generates CuPt-A was demonstrated. Observation of CuPt-A in $Al_xIn_{1-x}As$ in spite of the previous observation of TP-A in $Al_{0.5}In_{0.5}As$ is, therefore, explained by the surface-reconstruction change from (2x3) to (1x2) due to the alloy-composition change. References[1] For review of atomic ordering in III-V alloys, see the article by T.Suzuki; MRS Bulletin, 22(1997)p.33, Materials Research Society; see also the articles by A.Zunger (ibid.p.20) and by G.B. Stringfellow (ibid. p27). [2]A.Gomyo, M.Sumino, I.Hino, and T.Suzuki; Jpn. J. Appl. Phys., 34(1995)p.L469. [3]A.Gomyo, K.Makita, I.Hino, and T.Suzuki; Phys.Rev.Lett., 72(1994)p.673.

1:50 PM, Y2

Novel Ordered Structure in MBE GaAsSb Introduced by Surface Reconstruction Change During Growth: ANDREW GORDON NORMAN[1]; [1]National Renewable Energy Laboratory, Center for Measurements and Characterisation, 1617 Cole Boulevard, Golden, CO 80401 USA

Spontaneous atomic ordering on {111} planes has been observed in many alloy semiconductor layers, e.g. SiGe and ternary and quaternary III-V alloys, grown on close to (001) substrates. This atomic ordering is important as it leads to significant changes in the electrical and optical properties of the material. It is generally believed that the occurrence of this CuPt-like atomic ordering on {111} planes is related to the surface reconstruction present during growth. In particular subsurface strains associated with the arrangement of surface atom dimers induces an ordering of different sized atoms to occur during growth to minimize the elastic strain energy of the near surface region. It has been shown that by changing the surface reconstruction present during layer growth one can induce a different type of ordering in the growing layer e.g. $CuPt_A$ ordering on (111)A planes instead of $CuPt_B$ ordering on (111)B planes when growing AlInP on a c(4x4) as opposed to a $_\beta$2(2x4) reconstructed surface. In this paper we investigate the effect of changing the surface reconstruction of (001) molecular beam epitaxy (MBE) $GaAs_ySb_{1-y}$ layers during growth on the atomic ordering induced in the layers. For growth temperatures between 450 and 600ϒC and y⊕0.5 a $_\beta$2(2x4) reconstruction is present during growth of the $GaAs_ySb_{1-y}$ as determined by reflection high energy electron diffraction (RHEED). $CuPt_B$ ordering was observed in these layers by transmission electron diffraction (TED) studies. For growth temperatures greater than 600ϒC and y⊕0.7 the surface reconstruction was observed by RHEED to change to the high temperature α(2x4) structure. TED studies of these layers revealed the presence of a new ordered structure, not previously reported, in these layers induced by the different surface reconstruction present during growth. The new ordered structure observed is a periodic antiphase structure of CuAu ordering of the As and Sb atoms on {110} and {100} planes of the zinc-blende lattice. The unit cell of the ordered structure is $4d_{110}$ zinc-blende along the [110] zinc-blende direction, d_{110} zinc-blende along the [-110] zinc-blende direction and d_{001} zinc-blende along the [001] zinc-blende direction. An antiphase boundary (APB) occurs every two {110} zinc-blende spacings along the [110] direction. The structure therefore contains a periodic array of APBs along the [110] zinc-blende direction spaced apart by $2d_{110}$ of the zinc-blende structure. The generation of this new ordered structure appears to be associated with the occurrence of strained Ga dimers on the α(2x4) reconstructed surface that are rotated by 90ϒ with respect to the group V atom dimers on the $_\beta$2(2x4) reconstructed surface. These results provide fresh insight into the generation mechanism of atomic ordering during the epitaxial growth of semiconductor alloys.

2:10 PM, Y3

Radiative and Non-Radiative Processes in AlGaInP: N. J. CAIN[1]; D. W. Peggs[1]; D. J. Mowbray[1]; M. S. Skolnick[1]; P. C. Mogensen[2]; P. Blood[2]; S. Bland[3]; G. J. Jones[3]; R. Petrie[3]; [1]University of Sheffield, Department of Physics, Hicks Building, Hounsfield Road, Sheffield, South Yorkshire S3 7RH UK; [2]University of Wales Cardiff, Department of Physics and Astronomy, PO Box 913, Cardiff, South Glamorgan CF2 3YB UK; [3]Epitaxial Products International Ltd., Pascal Close, Cypress Drive, St. Mellons, Cardiff, South Glamorgan CF3 0EG UK

A study of the factors determining the quantum efficiency of the GaAs-latticed matched, wide band gap semiconductor AlGaInP is presented. The III-V alloy semiconductor AlGaInP can be grown latticed matched to GaAs for the composition $(Al_XGa_{1-X})_{0.5}In_{0.5}P$. By varying the Al composition, x, the direct band gap can be tuned over a range corresponding to wavelengths 640-550nm. $(Al_XGa_{1-X})_{0.5}In_{0.5}P$ is hence the material system of choice for red-green opto-electronic device applications. Whilst internal quantum efficiencies approaching 100% are obtainable for the end ternary $Ga_{0.5}In_{0.5}P$ (corresponding to an emission wavelength of 640nm), the addition of Al to achieve shorter wavelength emission results in a rapid decrease in efficiency. Such a behavior indicates an increasing non-radiative recombination rate with increasing Al composition. This may be an entirely extrinsic effect, resulting from increasing deep centre recombination. Alternatively, the effect of the deep centres may be enhanced by a reduced radiative lifetime when carriers transfer to the indirect conduction band minima as the direct-indirect band gap crossover is approached. This crossover, which occurs for x~0.5, provides an intrinsic contribution to the decrease in efficiency. An understanding of the relative importance of these two mechanisms (extrinsic and extrinsic-intrinsic) is vital if the efficiency of short wavelength devices based on the $(Al_XGa_{1-X})_{0.5}In_{0.5}P$ material system is to be optimized. The photoluminescence efficiency of a series of Al0.5In0.5P-(AlXGa1-X)0.5In $_{0.5}$P- $Al_{0.5}In_{0.5}P$ double heterostructures has been studied as a function of both Al composition and doping type in the active region. In addition, the photoluminescence efficiency of an $Al_{0.5}In_{0.5}$ P-$Ga_{0.5}In_{0.5}P$-$Al_{0.5}In_{0.5}P$ structure has been determined as a function of hydrostatic pressure. This latter measurement allows the direct and indirect band gap separation to be varied in a controllable way. Hence the intrinsic process (band structure) can be varied whilst the extrinsic process (deep level density) remains constant. A comparison of these two measurements (efficiency vs composition and efficiency vs pressure) therefore allows the relative contributions of the two factors determining the decrease in efficiency with increasing x to be deduced. In $Ga_{0.5}In_{0.5}P$ a long range crystal ordering of the group-III atoms may occur. This ordering can have a large effect on the electronic and optical properties of the material, including a reduction in the direct band gap energy and a splitting of the normally degenerate zone-centre valence band states. Despite its importance, the effects of ordering in $(Al_XGa_{1-X})_{0.5}In_{0.5}P$ have not been studied in detail. The results of a study of the effects of ordering on the optical and electronic properties of $(Al_XGa_{1-X})_{0.5}In_{0.5}P$ will be presented. Low temperature photoluminescence excitation (PLE) and polarized PLE are used to measure the order induced band gap reduction and valence band splitting respectively. The effects of ordering are investigated as a function of Al content, substrate orientation and doping type. This work is supported through the DTI/EPSRC LINK programme GLLAD (Green LEDs for Large Area Displays)

2:30 PM, Y4

Influence of Ordering on the Properties of GaInP/GaAs Heterojunction Bipolar Transistor Structures: Y. S. Huang[1]; W. D. Sun[1]; FRED H. POLLAK[1]; J. L. Freeouf[2]; I. D. Calder[3]; R. E. Mallard[3]; [1]Brooklyn College of the City University of New York, Physics Department and New York State Center for Advanced Technology in Ultrafast Photonic Materials and Applications, Brooklyn, NY 11210 USA; [2]Interface Studies, Inc., Katonah, NY 10536 USA; [3]Nortel Limited, Advanced Technology Laboratory, Ottawa, Ontario K1Y 4H7 Canada

We have investigated two GaInP/GaAs (001) heterojunction bipolar transistor structures, fabricated by organometallic chemical vapor deposition (OMCVD) and chemical beam epitaxy (CBE), using contactless electroreflectance, including the dependence of the signals on the polarization {[110] and [1-10]} of the incident radiation. The ordering parameters (η) deduced from the polarization dependence of the GaInP emitter signals are consistent with transmission electron microscope measurements. From the observed Franz-Keldysh oscillations we have evaluated the electric fields in the collector/base and emitter/base regions. For the same emitter doping level the emitter field in the more ordered OMCVD material (η = 0.3) is about 20 kV/cm smaller in relation to the CBE sample (η = 0. 18). We ascribe this difference to the influence of the piezoelectric field related to ordering. In general both the emitter (disordered material) and

collector fields are in good agreement with a calculation based on a comprehensive, self-consistent model, including the photovoltaic effect. Ordering in the GaInP leads to a band gap reduction (ΔE_{BGR}) and valence band splitting (ΔE_{VBS}), which can be determined from the band gap difference between light polarization along [110] and [1-10] . The quantity η can be estimated from either ΔE_{VBS} or ΔE_{BGR}. However, while a band gap variation could be due to either ordering or lattice mismatched, ΔE_{VBS} is the signature of ordering. If η deduced by these two approaches is the same the GaInP is lattice-matched to GaAs while if not tile difference in the band gaps can be used to evaluate the degree of lattice-mismatched. We find that both of our samples are lattice-matched.

2:50 PM, Y5

Ratio of Crystal-Field Splitting to Bandgap Reduction in Ordered GaInAs/InP: RALPH WIRTH[1]; Michael Geiger[1]; Joerg Porsche[1]; Ferdinand Scholz[1]; Andreas Hangleiter[1]; [1]University of Stuttgart, 4. Physikalisches Institut, Pfaffenwaldring 57, D-70550 Stuttgart, Baden-Wuerttemberg Germany

Ternary and quaternary semiconductor alloys tend to show long range ordering if certain growth conditions are employed. In particular the occurrence of CuPt-type ordering has been observed in a wide range of semiconductor alloys such as (Al)GaInP, GaAsSb, GaInAs(P), AlInP,GaAsP, AlInAs, and InPSb. However, most of the experimental work has been done in ordered GaInP. In ordered GaInP as well as in ordered GaInAs the ordering occurs in the group III sublattice where alternating Ga- and In-rich $\{111\}_B$planes are found, respectively. Since the ordering is imperfect, the degree of ordering is described by the ordering parameter η, where h=0 is the random alloy and η=1 is the perfectly ordered crystal. Among the most well-known changes in the band structure introduced by spontaneous ordering is the bandgap reduction compared to the random alloy and the valence-band splitting. Both have been subject to extensive investigations theoretically, whereas experimental data has been available mainly in the (Al)GaInP/GaAs material system up to now. All attempts to determine the degree of ordering by 'counting' atoms in actual samples have failed up to now. The specification of the degree of ordering hence is always depending in some degree on theoretical calculations, such as for example the value of the band-gap reduction for a perfectly ordered crystal. However, theoretical calculations may be compared and hence tested by comparison to experimental data using the ratio ζ of the bandgap reduction to the crystal-field splitting. We present the first measurements of ζ in the material system GaInAs/InP. Up to now such data has been available in the (Al)GaInP/GaAs material system only. We used the growth temperatures of 550 ϒC and 560 ϒC, tilts of the substrate towards $\{111\}_B$ from 2ϒ to 15ϒ and V-III ratios of 30 and 60 to obtain a series with various degrees of ordering. In addition these samples show single variant ordering, which has been tested by transmission electron diffraction. These samples have been investigated using low temperature absorption as well as excitonic bleaching experiments to determine the ordering induced bandgap reduction and valence-band splitting. Values as large as ≅45 meV for the bandgap reduction and @15 meV for the valence-band splitting have been observed. From these data we deduced the ratio ζ to be 1.8±0.4. This value is in good agreement with recent LDA corrected calculations presented by Wei and Zunger which yield a value of ζ=1.92. Assuming the theoretical value of 0.25 eV for the bandgap reduction of the perfectly ordered GaInAs crystal, we find ordering parameters for our samples up to η=0.44.

3:10 PM Break

3:30 PM, Y6

Lateral Composition Modulation in InAs/AlAs Short-Period Superlattices: Modulation Character, Formation Mechanisms and Properties: D. M. FOLLSTAEDT[1]; S. R. Lee[1]; E. D. Jones[1]; J. L. Reno[1]; A. G. Norman[2]; S. P. Ahrenkiel[2]; H. M. Cheong[2]; A. Mascarenhas[2]; R. D. Twesten[3]; J. Mirecki Millunchick[4]; [1]Sandia National Laboratories, Nanostructure & Semiconductor Physics, Mail Stop 1056, Albuquerque, NM 87185-1056 USA; [2]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401-3393 USA; [3]University of Illinois, Materials Research Laboratory, Urbana, IL 61801 USA; [4]University of Michigan, Materials Science & Engineering, Ann Arbor, MI 48109-2163 USA

We have investigated several fundamental properties of spontaneous lateral composition modulation in (InAs)n/(AlAs)m short-period superlattices (SPS), including the relation of microstructure to SPS structure and growth parameters, the amplitude of modulation, and electronic-optical properties. Key features of the growth and stability of modulated structures and of electronic properties in modulated systems are emerging from our detailed examinations. Both x-ray diffraction and cross-section TEM show strong modulation in SPS epilayers grown by MBE at 530°C on (001) InP with n+m ~4 monolayers. Intense satellite reflections and vertical In-rich columns are seen in specimens with near zero in-plane strain, but are not observed for large strains (|e| > 0.7%). Intense modulations and very regular spacings (~15 nm) also occur at moderate tensile strain (+0.4%), and the columns align with cusps in the growth surface. Such cusps are expected to be preferred sites in layers growing under tension for attaching the larger In atoms, and this interaction appears to reinforce the modulation. Both diffraction and TEM indicate a 2D nature to the modulation, with plan-view TEM showing In-rich columns (<30 nm across) modulated along two directions ~30° to either side of [1 10] in epilayers with tensile strain. Such modulation may be related to the change in the surface reconstruction from 2x1 for InAs to 1x2 for AlAs observed with in-situ RHEED during SPS growth; re-orienting surface dimer rows could also change the direction of fast lateral diffusion and produce modulation components in two orthogonal directions. Inadequate surface diffusion may be responsible for the loss of modulation observed when the growth temperature is reduced to 500°C. Evaluation of x-ray data for all (n,m) combinations studied indicates that modulation occurs only when n > 1.65 monolayers, suggesting that a critical InAs layer thickness is needed, perhaps to initiate modulation by first forming InAs islands. We are currently investigating this hypothesis. Energy-dispersive spectroscopy with characteristic x-rays from enriched regions indicates that the modulation amplitude is large, with local average compositions ranging from In0.38Al0.62As to In0.76Al0.24As. Raman spectroscopy shows phonon frequencies that imply similar compositions. Other TEM analyses also support such large modulation amplitudes. Magneto-luminescence measurements are consistent with carrier localization in a "quantum box" structure as might occur at In-enriched columns. The electronic properties and microstructure of modulated (InAs)n/(AlAs)m differ noticeably from those of InGaAs modulated along [110], where carriers move in enriched sheets extending for several tenths of micrometers along [1-10]. This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

3:50 PM, Y7

Correlation Between Domain Size and Band Gap in Ordered (GaIn)P: T. SASS[1]; H. Schmidt[2]; I. Pietzonka[1]; V. Gottschalch[1]; G. Wagner[1]; [1]Universität Leipzig, Fakultät f. Chemie u. Mineralogie, Linnestr. 3-5, D-04103 Leipzig Germany; [2]Universität Leipzig, Fakultät f. Physik u. Geowissenschaften, Linnestr. 3-5, D-04103 Leipzig Germany

The direct band gap of CuPt-type ordered (GaIn)P is known to depend on the degree of ordering, since the ordering effect causes a band gap reduction (BGR). However, the material is not only ordered, but also subdivided into domains of opposite phase relation by antiphase boundaries. The thickness of these ordered domains is taken into consideration for band structure calculations. We show that there is a distinct influence of the domain size on the direct band gap in (GaIn)P. The samples under investigation were grown by low-pressure MOVPE on nominally (001)GaAs-substrates with different angles of misorientation. The growth temperature (Tg) was varied from 595°C to 720°C to achieve different domain sizes. The thickness of the ordered domains was measured from transmission electron microscopy (TEM) dark field (DF) images taken from [110] cross-sectional specimen. Low temperature photoluminescence measurements were used to determine the direct band gap. The TEM investigations yielded a decrease of domain size with decreasing growth temperature. For temperatures below 650°C we find only average domain sizes less than 5nm for all substrate misorientations. Furthermore, the symmetry of the ordered (GaIn)P is reduced from trigonal to monoclinic symmetry, due to the shrinking of domain size. With increasing growth temperature at first the band gap energy decreases but after reaching a minimum it increases again. Pseudopotential band structure calculations based on the virtual crystal approximation were performed using supercells of the experimentally measured domain sizes. These calculations revealed a modification of the direct band gap with reduction of domain size, and thus symmetry, in ordered (GaIn)P. That means, a band gap reduction is not only caused by the degree of ordering, but also by a reduction of domain size. Thus, as is shown by the correlation of experimentally measured and calculated values of domain size and band gap energy, both, the band gap energy and the size of the ordered domains have to be known for a correct determination of the degree of ordering .

4:10 PM, Y8
Ordering Induced Optical Properties of AlGaInP Alloys: MATHIAS SCHUBERT[1]; Heidemarie Schmidt[1]; Torsten Sass[2]; Ines Pietzonka[2]; Volker Gottschalch[2]; Bernd Rheinländer[1]; Reinhard Schwabe[1]; [1]University Leipzig, Faculty of Physics and Geoscience, Department of Semiconductor Physics, Linnestrasse 5, Leipzig, Saxony D-04103 Germany; [2]University Leipzig, Faculty of Chemistry and Mineralogy, Department of Semiconductor Chemistry, Linnestrasse 3, Leipzig, Saxony D-04103 Germany

We use a transmission and reflection dark-field modulation-spectroscopy technique to study and determine order-dependent critical point variations and anisotropy in spontaneously ordered AlGaInP. In particular, we report direct-gap reduction and valence-band splittings as a function of the Al-composition in AlGaInP alloys lattice matched to GaAs. Transmission electron microscopy investigations reveal that two effects cause changes of the optical fingerprints of the alloys: (i) the degree of ordering within the ordered domains, and (ii) a symmetry change from trigonal to monoclinic due to decrease in the size of the ordered domains. The average domain size depends on the growth conditions and can be determined from dark-field images. Empirical pseudo-potential band structure calculations (virtual crystal approximation) which account for the experimentally determined domain sizes (supercell calculations involving up to 16 monolayers) prove that band-gap reduction and valence band splitting in GaInP and AlInP depend on the size of, and the degree of ordering within the ordered domains.

4:30 PM, Y9
Late News

4:50 PM, Y10
Late News

FRIDAY AM

Friday AM, June 26, 1998

Session Z. Growth and Electrical Characterization of Quantum Dots and Superlattices

Room: E316
Location: Thornton Hall

Session Chairs: Richard Mirin, NIST , Boulder, CO 80303 USA; Kanji Yah, Hokkaide University, Research Center for Interface Quamtam Electronics, Kitatcu, Sapporo 060-8628 Japan

8:20 AM, Z1
Pseudopotential Calculations of Excitonic Transitions in Semiconductor Quantum Dots: InP, InAs, CdSeAnd InAs/GaAs: ANDREW J. WILLIAMSON[1]; Lin-Wang Wang[1]; Hiauxiang Fu[1]; Alex Zunger[1]; [1]National Renewable Energy Laboratory, Solid State Theory Group, 1617 Cole Blvd., Golden, CO 80401 USA

The recent combination of narrow size distributions and size selective photoluminescence excitation spectroscopy has produced a rich set of experimental data for excitonic transitions in semiconductor quantum dots. The classification of these excitonic transitions provides a stringent test for current theoretical models. We present results of pseudopotential calculations of single-exciton states in both free standing InP, InAs and CdSe quantum dots and InAs dots embedded within a GaAs barrier, grown by the Stranski Krastanov technique. In both cases, excellent agreement with recent experiments [1-3] is obtained. For the free standing dots, we construct a theoretical optical absorption spectra using a two step process. First, we solve for ~40 single-particle electron and hole states using a screened atomic pseudopotential Hamiltonian [4], solved within a plane wave basis using the Folded Spectrum Method [5]. We then calculate the electron-hole Coulomb energy [6] for each of the ~1000 possible single particle excitations and weight each of these possible transitions by its dipole transition probability. Using a recently developed method for analyzing the angular momentum of each electron and hole state, we compare our electron and hole states with those found using the standard k.p method. We find that: (i) there are more pseudopotential hole states than k.p states within a given energy range, (ii) our pseudopotential optical transition peak assignment agrees with the k.p for the lowest few peaks, but not for the higher peaks, (iii) strong non-spherical character exists in the pseudopotential wavefunctions, and even-odd symmetry mixing is allowed. For the InAs/GaAs Stranski-Krastanov dots we use the same empirical pseudopotentials to investigate the lowest optical transitions as a function of both the dot size and external hydrostatic pressure. We compare the number bound electron and hole states, with recent theoretical and experimental values. Finally, we use our calculations to verify a new proposed method [3] for using high pressure photoluminescence measurements to extract the electron and hole binding energies. [1] D.J. Norris, A.L. Efros, M. Rosen and M.G. Bawendi, Phys. Rev. B 5316347 (1996)[2] U. Banin and A.P. Alivisatos, in preparation[3] I.E. Itskevich, S.G. Lyapin, I.A. Troyan, P.C. Klipstein,L. Eaves, P.C. Main and M. Henini, submitted to Appl. Phys. Lett. [4] J. Kim, A.J. Williamson, L.W. Wang, S.H-. Wei and A. Zunger, submitted to Phys. Rev. B[5] L. W. Wang and A. Zunger, J. Chem. Phys. 100, 2394 (1994). [6] A. Franceschetti and A. Zunger, Phys. Rev. Lett. 78, 915 (1997).

8:40 AM, Z2+
Growth and Characterization of Vertically Stacked InAs Quantum Dot Structure: QIAN GONG[1]; Jiben Liang[1]; Zhanguo Wang[1]; [1]Institute of Semiconductors, Laboratory of Semiconductor Materials Science, P. O. Box 912, Beijing, 100083 China

Vertically stacked InAs quantum dot (QD) structures were grown by molecular beam epitaxy (MBE) on semi-insulating (001)-GaAs substrate. All the four structures consist of five vertically stacked InAs quantum dot sheets with the constant thickness of 2.5 monolayers (MLs), while the thickness of the GaAs spacers are 3, 5, 9, and 15 nm for each sample. Photoluminescence (PL) measurements were performed at 15 K. The Gaussian-shaped peaks of QD emission at different positions was observed from all the samples with the different GaAs spacers in thickness d. For d = 3, 5, 9, and 15 nm, the PL peaks were at 1.212, 1.215, 1.204, and 1.215 eV, respectively. The little change in the energy of PL peak demonstrates that variation of the GaAs spacer thickness has little effect on the PL peak positions. This result is in contrast to the report that the PL peak shifts towards lower energy with the increasing the GaAs spacer thickness. The FWHM and integrated PL intensity were obviously dependent on the GaAs spacer thickness d. When d decreases from 15 nm to 5 nm, FWHM reduces from 85 meV to 38 meV, while in the structure with 3 nm GaAs spacer the FWHM increases to 42 meV. The dependence of integrated PL intensity on the spacer thickness d is that when d decreases from 5 to 3 nm, the integrated PL intensity decreases by more than one order. However, the integrated PL intensity is of the same order for the structures with d = 5, 9, and 15 nm, and the PL efficiency in the structure with d = 5 nm is the highest. It is worth notice that 5-nm is the optimum thickness for GaAs spacer, resulting in the highest PL efficiency and a minimal PL line width. Transmission electron microscopy shows self-organization of InAs dots in vertical direction influenced strongly by the thickness of GaAs spacer. The dots in sample with 5-nm or 3-nm GaAs spacer are aligned vertically in a line, leading to narrow PL FWHM. On the other hand the alignment of dots in structure with 15-nm GaAs spacer is not obvious. Dislocations due to the strain accumulation are found in the sample with GaAs spacer of 3-nm and PL quenching could be explained in terms of degraded crystal quality.

9:00 AM, Z3
Sub-monolayer Deposition of In, Ga, and as to Form 1.3 μm Wavelength Quantum Dots: DIANA L. HUFFAKER[1]; G. Park[1]; O. Shcheckin[1]; D. G. Deppe[1]; [1]University of Texas at Austin, Electrical and Computer Eng., 10100 Burnet Rd., Bldg. 160, M.S. R9900, Austin, TX 78758 USA

In this talk, we describe the influence of material deposition conditions on the formation of self-assembled InGaAs/GaAs quantum dots (QDs) for 1.3μm emission. We show that good electroluminescence efficiency and narrow linewidth can be achieved at a 1.3 μm wavelength using sub-monolayer depositions of

In, Ga and As. We also show, for the first time, the influence of growth method on dot size, dot density and ground state emission wavelength. A wide range of growth techniques have been studied including bulk growth of $In_{0.50}Ga_{0.50}As$, alternating monolayers of InAs and GaAs as well as sub-monolayer deposition of In, Ga and As. The dots resulting from this study have been characterized by atomic force microscopy (AFM) and electroluminescence spectrum and efficiency measurements. We show that for the same In composition (50%) and same total amount of QD material growth (10ML), QDs formed by submonolayer deposition are much larger (500Å), less dense ($1x10^{10}$ dots/cm^2) and have an increased ground state emission wavelength (1.32 μm) compared to QDs formed by either bulk growth (250Å, $1x10^{11}$ dots/cm^2, 1.21 μm) or alternating monolayers of InAs and GaAs (350Å, $5x10^{10}$ dots/cm^2, 1.22 μm). This difference in the dot density and size indicate that the In and Ga growth in the absence of As allows a larger migration distance for atoms on the growth surface. For the same 10 ML QD material thickness, AFM also indicates the presence of QD coalescence and defects in the bulk-growth QD sample which are not present in the samples grown by submonolayer deposition. These defects are associated with a reduction in output efficiency. The alternating and separate supply of the column III and column V constituents has been previously identified as leading to large QDs with longer emission wavelength.[1,2] However, crystal quality as influenced by strain and dislocations is not clear in the earlier work. In this talk we show that the electroluminescence efficiency is in fact quite sensitive to the column III submonolayer deposition thickness and that the optimum sub-monolayer thickness is 0.25 ML. Using this active region in an LED, we have measured electroluminescence efficiency of 0.22% at 1.32 μm under room temperature, CW operation which is similar to our best In0.20Ga0.80As quantum well active regions. At low current densities, the electroluminescence spectral linewidth is 30 meV which also indicates good QD size uniformity. We will also discuss ongoing work to increase dot density and dot size uniformity, both of which are important for 1.3 μm QD VCSELs on GaAs. REFERENCES1. K. Mukai, O. Nobuyuki, S. Mitsuru, and S. Mamazaki, "Self-formed In0.50Ga0.50As quantum dots on GaAs substrates emitting at 1.3μm," Jpn. J. Appl. Phys., vol. 33, pp. L1710-L1712, 1994. 2. R.P. Mirin, J.P. Ibbetson and K. Nishi, A.C. Gossard and J.E. Bowers, "1.3 photoluminescence from InGaAs quantum dots on GaAs", Appl. Phys. Lett., 67, pp. 3795-3997, 1995.

9:20 AM, Z4+

Reflection High Energy Diffraction Study of the Shape of InAs/GaAs Quantum Dots: HAO LEE[1]; Peter C. Sercel[2]; [1]University of Oregon, Physics Department, Materials Science Insititute, Eugene, OR 97403 USA; [2]University of Oregon, Physics Department, Eugene, OR 97403 USA

It has long been understood that the presence of facetted islands should cause the appearance of additional streaks in the RHEED pattern not normal to the nominal substrate plane, due to diffraction from the island facet planes. Indeed, in the case of self-organized InAs and InGaAs self-assembled dots (SADs) grown on (001) GaAs, Nabetani and co-workers have shown that the RHEED pattern taken along the [1-10] azimuth shows well-defined chevrons with an included angle of 50° pointing upwards towards the substrate shadow edge. This information was used to infer the existence of {113} facet planes[1,2]. However, an analysis based upon kinematic diffraction theory indicates that, were the InAs islands bounded by {113} facets, rather than the upwards pointing chevrons which are observed experimentally, one would expect to observe either crosses, or chevrons in opposed directions for different diffraction orders. To reconcile this discrepancy, we studied the RHEED patterns of InAs SADs as a function of azimuth angles[3]. We found that RHEED patterns along the [3-10] and [1-30] azimuths show off-normal streaks directed at an angle of 28° from the [001] direction, consistent with reflections from facets of the {136} family. RHEED patterns measured along the orthogonal [310] and [130] azimuths show no off-normal streaks, and no streaks were observed at any other azimuth. Identical features are observed in RHEED studies of $In_{0.5}Ga_{0.5}As$ quantum dots grown in our chamber. Our observations suggest that InAs SADs possess a C_{2v} pyramidal geometry with four {136} bounding facets. The structure has a parallelogram base, with base edges parallel to the [3-10] and [1-30] directions, and a long axis along [1-10]. The length:width:height ratio is 2:1: 2/6. The model accounts for the chevrons observed in the [1-10] azimuth and is consistent with the AFM images of InGaAs quantum dots reported by Mirin and co-workers[2]. The implications of our result to the electronic structure of SADs as well as to the formation mechanism will be discussed. [1]Y. Nabetani, T. Ishikawa, S. Noda, and A. Sasaki, J.Appl. Phys. 76, 3347 (1994). [2] R.P. Mirin, J.P. Ibbetson, K. Nishi, A.C. Gossard, and J.E. Bowers, Appl. Phys. Lett. 67, 3795 (1995). [3]H. Lee, R. Lowe-Webb, W. Yang, and P. C. Sercel, Appl. Phys. Lett. 72, 812 (1998).

9:40 AM, Z5

InAs Quantum Dot Spatial Ordering Using A Subsurface InAs Island Superlattice: G. S. SOLOMON[1]; S. Komarov[2]; J. S. Harris[2]; [1]Stanford University, ERATO Quantum Fluctuation Project, 76 South Ginzton Laboratory, Stanford, CA 94305-4085 USA; [2]Stanford University, Solid State Photonics Laboratory, Stanford, CA 94305-4075 USA

The formation of quantum dots by strain-induced islanding in lattice mismatched epitaxial growth has provided a simple, lithograph-free method to produce dense ensembles of quantum dots. This self-organized approach has been effectively used to investigate the 0-D structure in the dot ensembles and to create optoelectronic devices with improved operating characteristics. However, nearly all of these results involve random arrays of islands with slightly varying sizes, and the quest for atomic-like ensembles either ordered or random has not been demonstrated by this approach. To this end we have investigated the increased size and spatial ordering that results from employing a superlattice of InAs island layers below the active quantum dot layer. Both theoretical and experimental results have shown that increased size and spatial ordering can result in this system.[1,2] Under certain conditions, predominately with small numbers of island layers, well-aligned columns of islands are present. Electronic coupling between islands in individual columns has been demonstrated [3] and implemented in quantum dot lasers.[4] When a large number of island layers are deposited the strain created by adjacent columns interacts to create a surface strain distribution. The interaction of columns has been observed by cross-sectional STM.[5] Under certain conditions the strain distribution becomes a template that can lead to spatial ordering of the new island layer. We have investigated the limits of this ordering in the InAs/GaAs system by the deposition of up to 75 dot layers under various MBE growth conditions. We have used Fourier transform and autocovariance techniques to analyze the atomic-force microscopy data of surface islands. We have determined that under certain conditions a well ordered nearest neighbor arrangement is optimized, and second and third nearest neighbors are present. Through simulation of the autocovariance data we quantitatively determine the extend of nearest neighbor ordering. Although nearest neighbor ordering is present a surface lattice of dots is generally inhibited because of a lack of complete translational symmetry; however, some directionally dependent translational symmetry is present under certain conditions. We show that the lack of complete translational symmetry is due to the competing processes of surface diffusion and the subsurface strain which are specific to III-V materials and the MBE growth process. 1. J. Tersoff, C. Teichert, and M. G. Lagally, Phys. Rev. Lett. 76, 1675 (1996). 2. G. S. Solomon and J. S. Harris, Jr., J. Cryst. Growth 117 (1997). 3. G. S. Solomon, J. A. Trezza, A. F. Marshall, and J. S. Harris, Jr., Phys. Rev. Lett. 75, 2542 (1995). 4. F. Heinrichsdorff, M. -H. Mao, N. Kirstaedter, A. Krost, D.Bimberg, A. O. Kosogov, P. Werner, Appl. Phys. Lett., 71, 22 (1997). 5. G. S. Solomon, W. Wu, J. R. Tucker and J. S. Harris, Jr. in Physica E: Low-dimensional Systems and Nanostructures (in press).

10:00 AM Break

10:20 AM, Z6+

Thermal and Tunnel Emission from InAs Quantum Dots Investigated by Deep Level Transient Spectroscopy: CHRISTIAN M. A. KAPTEYN[1]; Frank Heinrichsdorff[1]; Marius Grundmann[1]; Dieter Bimberg[1]; [1]Technische Universität Berlin, Institut für Festkörperphysik, Hardenbergstr. 36, Berlin D-10623 Germany

We probe the properties of self-organized InAs quantum dots using deep level transient spectroscopy (DLTS). Electron emission from a triple layer of vertically coupled quantum dots in a GaAs matrix grown by metal organic chemical vapour deposition (MOCVD) has been investigated. The devices studied are p+/n junctions with the quantum dots located outside the depletion region of the nGaAs at zero bias. We observe an ensemble-averaged thermal activation energy of 90meV for electrons. From the DLTS signal a dot density of about $N_{QD}=1.9*10^{10}cm^{-2}$ is derived in agreement with plan-view TEM images. Towards lower temperatures a broad continuum is present in the DLTS signal, indicating a contribution of temperature independent tunnel emission from the quantum dots. With increasing detection bias the relative strength of the tunneling signal is enhanced and eventually dominates the DLTS spectrum as expected from theoretical modelling. Upon varying filling pulse bias and detection bias of

the DLTS measurement we demonstrate the possibility to study sub-ensembles of quantum dots with a certain range of activation energies.

10:40 AM, Z7

Capacitance Measurements of Self-Assembled GaSb Quantum Dots: R. MAGNO[1]; B. R. BENNETT[1]; E. R. Glaser[1]; M. E. TWIGG[1]; [1]Naval Research Laboratory, Electronics Science and Technology Div., 4555 Overlook Ave SW, Code 6876, Washington , DC 20375 USA

Capacitance-voltage (CV) and deep level transient spectroscopy (DLTS) measurements have been made to study the electronic properties of self-assembled GaSb dots that were grown on GaAs by molecular beam epitaxy (MBE). Photoluminescence (PL) studies of GaSb dots grown in the same MBE system indicate that they have a type II band structure with the holes trapped in the GaSb dot.[1] Because the GaSb dots trap holes, they were placed in the depletion region on the p side of a GaAs n+p junction. Among the samples were two control junctions, one with no dots and another with a one monolayer (ML) GaSb wetting layer. Two samples with dots were prepared by depositing three ML of GaSb at either 170 nm or 250 nm from the n+p junction. Atomic force microscopy measurements of three ML GaSb dots indicate they have an average height of 3 nm, diameter of 30 nm , and density of ~10^{10} cm^{-2}. The dots manifest themselves as a step in the capacitance in a CV measurement. The details of the shape of the step depend on the sample's temperature and the excitation frequency of the capacitance meter. The CV data have been modeled by integrating Poisson's equation over the depletion region with the assumption that the dots are a plane of charge. The amount of charge on the dots depends upon the distribution of energy levels in the band gap. The emission and capture rate for trapped holes are important as they determine how the trapped charge responds to the capacitance meter. The DLTS spectra are found to depend upon the bias and pulse heights applied to the diodes. This is expected as the dots are located in a small portion of the depletion region, and the part of the depletion region being sampled depends on the bias and pulse height. A peak with an activation energy of about 0.3 eV has been found for a limited range of bias and pulse heights, which suggests that it is associated with holes in the dots. These holes may be related to the 1.15 eV band found in PL measurements.[1] The DLTS data indicate the presence of several deep defects. Based on the range of bias and pulse heights for which they are found they are more likely to be spread over a larger portion of the depletion region than the 0.3 eV peak. This suggests that they are associated with defects in the GaAs near the dots. *Work supported in part by the Office of Naval Research1E. R. Glaser, B. R. Bennett, B. V. Shanabrook, and R. Magno, Appl. Phys. Lett. 68, 3614 (1996).

11:00 AM, Z8

Metastable Population of InAs/GaAs State in Self Assembled Quantum Dots: M. M. SOBOLEV[1]; A. R. Kovsh[1]; V. M. Ustinov[1]; A. Yu. Egorov[1]; A. E. Zhukov[1]; [1]A.F. Ioffe Physical Technical Institute, 26 Polytechnicheskaya ul., 194021, St. Petersburg, Russia

Formation of bistable dipoles due to Coulomb interaction between carriers localized in InAs/GaAs vertically coupled quantum dots (QD) and point defects located in QDs was first reported previously [1,2]. In the present work we report on controlled and reversible metastable population of energy states in quantum dots as a function of temperature of isochronous anneal and bias-on-bias-off cooling conditions in a structure containing one plane of quantum dots. The structure studied by capacitance-voltage(C-V) and deep level transient spectroscopy (DLTS) contained QDs formed as the result of deposition of 3 MLs of InAs embedded into GaAs(p=3x$10^{16}$$cm^{-3}$) grown on n+ <100> GaAs substrate and covered with n+ GaAs contact layer. C-V profiles and DLTS spectra clearly demonstrated spatial localization of carriers associated with QDs. To study DLTS signal originated from the QDs and the layers below and above QDs, we applied different combinations of the bias voltages Vb and filling pulse voltages Vf . Thermal activation energy of the H1 level associated with the hole emission from QDs was 240 meV. The position of the H1 peak in DLTS spectra depended on values of Vb .We attribute the observed energy shift to the carrier tunneling through the potential barrier reduced by the p-n junction electric field. In addition, the height of the H1 peak depended on conditions of preliminary annealing, cooling, and optical illumination. After isochronous annealing at T>250K and under reverse bias voltage the height of the H1 peak increased, whereas after isochronous annealing at T<250K and Vb=0 the height of the H1 peak decreased. Simultaneously with the variation of the H1 peak height we observed the change in the effective carrier density in the QD region after isochronous annealing at Vb=0 or Vb<0. Illumination also changed effective carrier density in QDs. We attribute this effect to the change in the position of the Fermi level owing to the capture of holes on selftrapped defects after isochronous annealing at Vb=0. A certain concentration of deep traps (1x10^{14}-1x10^{15} cm^{-3}) has been revealed in the vicinity to QDs. Our experimental results allow us to assume the formation of complex metastable center by deep traps in GaAs. The carrier emission from these deep traps proceeds to the band states as well as by multiphonon tunnel transition. It has been found that the position ofmaximum of the wide DLTS peak associated with this complex metastablestate also depended on the temperatures of isochronous annealing andbias-on-bias-of cooling conditions. [1] M.M.Sobolev, A.R.Kovsh, V.M.Ustinov , A.Yu. Egorov, A.E. Zhukov,M.V.Maximov, N.N.Ledentsov, Materials Science Forum (1997). [2] M.M.Sobolev, A.R.Kovsh, V.M.Ustinov , A.Yu. Egorov, A.E. Zhukov,M.V.Maximov, N.N.Ledentsov, Semiconductors 31 (1997) 1074.

11:20 AM, Z9

Investigation of Dynamic Properties of Self-Assembled InAs/GaAs Quantum Dots: PAVEL N. BROUNKOV[1]; Alexandra A. Suvorova[1]; Alexey R. Kovsh[1]; Victor M. Ustinov[1]; Samouil G. Konnikov[1]; L. Eaves[2]; Peter C. Main[2]; [1]A.F.Ioffe Physico-Technical Institute, Department of Physics of Semiconductor Heterostructures, Polytechnicheskaya 26, St-Petersburg 194021 Russia; [2]University of Nottingham, Department of Physics, University Park, Nottingham, UK NG7 2RD UK

We report a capacitance-voltage (C(V)) study of a structures with a Schottky barrier on a n-type layer containing an array of self-assembled quantum dots (QDs). There is a plateau in the C(V) characteristic related to the discharging of the QDs. The capacitance is measured by superimposing a small oscillation signal V_{osc} , frequency f , on the DC reverse bias V_{rev}. Note that V_{osc} modulates the charge both at the edge of the space charge region (dQ_{3D}) and at the point where the Fermi level crosses the electron level in the QDs (dQ_{qd}). In the region of the capacitance plateau the change in the space-charge-region width dW due to the increment of the reverse bias dV becomes so small that dQ_{qd} is larger than dQ_{3D}. As the temperature is lowered from 70 K to 4.7 K, the quantum part of capacitance C_{qd} decreases, despite the fact that the occupation of QDs tends to be saturated and at T = 4.7 K C_{qd} disappears entirely. We have found that it is due the fact that the thermionic emission rate of electrons (e_n) from the QDs is much lower than the angular measurement frequency $2\pi f$, i.e. freezing-out of electrons on QD levels takes place. The thermionic emission rate depends exponentially both on the temperature and the energy of the QD electron levels, therefore through the change of the measurement frequency and the temperature we can control the quantum part of capacitance C_{qd} . Temperature dependence of the capacitance C(T) has a characteristic step if the V_{rev} lies inside capacitance plateau on C(V) plot. Temperature of the recovery of the C_{qd} depends on the measurement frequency and happens when $e_n = 2\pi f$. From Arrehnius plot it is possible to extract energy activation and effective cross-section of levels in QDs. Since the array of self-assembled QDs has a Gaussian density-of-states, we can study different part the QD energy spectra through the change of the reverse bias. As the V_{rev} is increased the position of the capacitance step goes to higher temperature. It means the more deeper states contributes to the quantum part of capacitance C_{qd}. We have investigated the frequency-dependent C(V) characteristics of an n-GaAs structure containing self-assembled InAs QDs. It was found that the C(T) characteristics of the quantum part of capacitance C_{qd} depend on the relation between the thermionic emission rate e_n of electrons from QDs and the angular measurement frequency $2\pi f$. Analysis of the capacitance spectra can give us information about dynamic parameters of the QDs. Through the change of the V_{rev} it is possible to study different part of the QD energy spectra. Comparison of single layer and stacked QD grown both in p-type and n-type matrices will be made.

11:40 AM, Z10+

Ballistic Electron Spectroscopy of semiconductor Quantum Devices: CHRISTOPH M. RAUCH[1]; Gottfried Strasser[1]; Erich Gornik[1]; [1]Technical University Vienna, Solid State Electronics, Floragasse 7, Vienna A-1040 Austria

The electric field dependent transport in semiconductor superlattices has been investigated. We use the concept of a hot electron transistor to measure the transmission of an undoped biased superlattice. When a uniform electric field is applied to the superlattice, the quasi-continuous minibands break up into a ladder of discrete Wannier-Stark states. This localization of the electron wave function has direct consequences on the ballistic electron transport. In our devices a tunable electron beam with a normal energy distribution of about 15meV in width is generated by a tunneling barrier, passes the superlattice after traversing a thin

highly doped GaAs region and an undoped drift region. The collector current is measured as a function of the injection energy. The probability for an injected hot electron to cross the superlattice reflects the transmission of the miniband under bias condition and can be considered to be proportional to the measured transfer ratio a=IC/IE. Recently, we have used the technique of hot electron spectroscopy to measure the positions of minibands and minigaps of field free undoped superlattices. For the first time, the localization of the electron wave functions of superlattice states under bias leading to a collapse of the transmission can be observed directly. Two molecular beam epitaxy grown samples with different superlattice lengths have been investigated. While the transfer characteristics of a five period superlattice is symmetric for accelerating and decelerating fields, the transmission of a ten period superlattice shows a clear field dependent asymmetry. The onset of scattering induced transport through the superlattice is clearly evident. The transition between coherent and incoherent band transport in superlattices is observed. We suggest that the observed coherence length of 80 nm is primarily limited by well width fluctuation. The experimental results are reproduced by a calculation based on a transfer matrix method including interface roughness. A detailed analysis of the miniband transmission gives us the coherence length and the scattering time of the electrons in the superlattice. The interface structure is obtained by a comparison to theory. Island sizes of the order of 10 nm are suggested. Consequently we claim that the interface roughness is the limiting factor of the electron mean free path. Furthermore we achieved population inversion by injecting electrons selectively into the second miniband of such superlattices using the hot electron transistor.

Friday AM, June 26, 1998

Session AA. Materials Integration: Wafer Bonding and Compliant Substrates

Room: 009
Location: Olsson Hall

Session Chairs: April S. Brown, Georgia Institute of Technology, Dept. of Electrical Engineering, Atlanta, GA USa; Thomas Kuech, University of Wisconsin, Dept. of Chemical Engineering, Madison, WI USA

8:20 AM, AA1
Integration of Multiple-Wavelength Light Sources by Wafer Fusion: P. D. FLOYD[1]; C. L. Chua[1]; D. P. Bour[1]; D. W. Treat[1]; [1]Xerox Palo Alto Research Center, Electronic Materials Laboratory, Palo Alto, CA 94304 USA

Wafer fusion is an attractive method of combining semiconductors of different lattice constant into a single epitaxial structure [1][2]. In this work, we demonstrate fusion of GaAs-based laser structures to GaN-based light-emitting heterostructures. Successful operation of infrared lasers fused to functioning GaN LEDs is achieved. The AlGaInAs/AlGaAs QW laser diode heterostructures were grown by low-pressure organometallic vapor phase epitaxy (OMVPE) on misoriented n+ GaAs substrates. The GaN LED and laser structure were grown by OMVPE on A and C-face sapphire substrates, respectively. The laser consists of a InGaN/GaN MQW surrounded by AlGaN and capped with a GaN layer. The laser structure did not function due to insufficient of p-doping. The fully-functioning LED structure consists of a single InGaN/GaN QW capped with a p-GaN layer. The heterostuctures were fused at 600-650 ϒC in a H_2 ambient, while under uniaxial pressure [3]. To fabricate the lasers, the GaAs substrate was selectively etched, leaving the AlGaInAs QW laser structures on GaN. Mesas were defined to form ridge wave-guides for the QW lasers as well as the InGaN/GaN LEDs. Finally the integrated devices were scribed into bars. The AlGaInAs QW lasers fused to GaN laser structures were tested using a pulsed current source. A 20 x 750 μm laser operated with a threshold Current (I_{th}) of 60 mA and external efficiency (η_d) of 23 %/facet at 820 nn. Typical I_{th} are 60-90 ma and typical η_d values are 10-15%/facet. AlGaInAs QW laser structures fused to InGaN/GaN LED structures were used to form closely-spaced (75 μm) infrared lasers and blue LEDs. AlGaInAs QW lasers (15 x 510 μm), operated with a I_{th} of 20 mA and η_d of 15.5 %/facet at about 820 nm. The adjacent InGaN/GaN LED emitted at 458 nm. Facets formed by scribing of the sapphire substrate are often rough and not perpendicular to the waveguide. This increases I_{th} and limits η_d. Improved facet formation should improve I_{th} and η_d. This work was supported in part by the Dept. of Commerce, Advanced Technology Program Grant No. 70N AN82H1241. [l] R.J. Ram et at, J. Appl. Phys., 78, 4227, 1995[2] Y.H. Lo et al, Appl. Phys. Lett. 62, 1038, 1993[3] Z.I.. Liao and D.E. Mull, Appl. Phys. Lett. 56, 737, 1990

8:40 AM, AA2+
First Demonstration of A GaAs/GaN Fused p-N Heterojunction: LEE S. MCCARTHY[1]; James G. Champlain[1]; Peter Kozodoy[1]; Giacinta Parish[1]; R. Kehl Sink[1]; Umesh K. Mishra[1]; [1]University of California, Santa Barbara, Electical and Computer Engineering Dept., Engineering I, Santa Barbara, CA 93106 USA

We have demonstrated the first fused GaAs/GaN p-N heterojunction. Ideality factors as low as 1.14 have been measured on fused diodes. The motivation for this research is to investigate the properties of a high mobility semiconductor (GaAs) in conjunction with a large breakdown semiconductor (GaN) for applications in solid-state devices such as heterojunction bipolar transistors (HBTs). Difficulties in fabricating the GaAs/GaN heterojunction using conventional growth methods has spurred the use of fusion to achieve this end. Beryllium doped p-type (100) GaAs was grown on a semi-insulating (SI) GaAs substrate by solid-source molecular beam epitaxy (MBE). Silicon doped N-type (0001) GaN was grown on sapphire by metal-organic chemical vapor deposition (MOCVD). The surfaces to be fused were cleaned, and dipped in hydrofluoric acid (HF) before being placed in a graphite fusion fixture. The fixture was designed to apply uniform pressure to the fusion interface during the high temperature heating cycle. The samples were heated to 750ϒ C in a nitrogen ambient, then returned to room temperature over the course of several hours. After fusion of the two wafers, the SI GaAs substrate was removed using a wet chemical spray etch. The etch stopped on a sacrificial AlAs layer which was then removed with HF, leaving the 1um p-type GaAs epilayer fused to the N-type GaN on sapphire. Reactive Ion Etching, (RIE) was then used to define mesas, allowing for the fabrication of p-N diodes. Contacts were made to the GaAs and GaN layers, and preliminary electrical characterization including capacitance-voltage (C-V) and temperature-dependent current-voltage (I-V) measurements were made.

9:00 AM, AA3+
Structural and Chemical Analysis of The GaAs/InP Wafer Bonded Interface: K. ALEXIS BLACK[1]; Sheila K. Mathis[1]; Patrick Abraham[2]; John E. Bowers[2]; Evelyn L. Hu[1]; [1]University of California, Santa Barbara, QUEST, Materials Department, Santa Barbara, CA 93106 USA; [2]Univeristy of California, Santa Barbara, Electrical and Computer Engineering Department, Santa Barbara , CA 93106 USA

Wafer fusion, the bonding of materials through the application of pressure and temperature, has resulted in enormous benefits to device operation. For example, the fusing of GaAs/AlAs Bragg reflectors to an InP-based active region has resulted in record performance of vertical cavity surface emitting lasers operating at 1.55 μm and 1.3 μm wavelength. Despite the demonstrated capabilities of the wafer fusing process, substantial progress must be made in the fundamental characterization and understanding of the fusing process itself and the resulting interface quality. In this paper, the structure and chemistry of the GaAs/InP wafer fused interface is examined by a combination of high resolution microscopy and Secondary Ion Mass Spectroscopy (SIMS). Such analysis techniques reveal the presence of periodically aligned elongated features, possibly microvoids or a second phase of material, as well as the accumulation of both dopants and organic contaminants at the fused interface. Broad area SIMS indicates the presence of a continuous, uniform oxide localized at the interface. Chemical passivation of the semiconductor surfaces before fusion bonding was also investigated in order to both elucidate the mechanism of fusion as well as to optimize the electrical characteristics of the fused junction. Wet chemical passivation schemes producing both hydrophobic and hydrophilic semiconductor surfaces, as well as dry passivation techniques such as antimony capped growths were explored. Bonding conditions were varied to assess the effects of applied pressure and degree of off (100) axis miscut of the starting wafers on the periodicity and alignment of interfacial features. InP wafers of both 0.2° and 2° intentional misorientation from the (100) axis, and GaAs wafers of 21.9° misorientation were fused and analyzed by both plan view and cross-sectional transmission electron microscopy. We will attempt to correlate these structural

and chemical properties with macroscopic measurements such as junction resistance.

9:20 AM, AA4

Single Crystal Silicon-On-Sapphire by Wafer Bonding: PAUL THOMAS BAINE[1]; H S Gamble[1]; B M Armstrong[1]; S JN Mitchel[1]; [1]Queens University Belfast, Electrical Electronic Engineering, Ashby Building, Stranmillis Road, Belfast, Co. Antrim BT9 5AH Northern Ireland

Silicon-On-Sapphire (SOS), previously achieved by epitaxial growth, improves thermal and high frequency performance of interconnects as compared to Silicon-On-Insulator (SOI). Applications for SOS include high speed, low power CMOS integrated circuits.. However performance is degraded due to dislocations resulting from this silicon epitaxial growth process. Dislocation free SOS can be achieved through wafer bonding and thinning technologies. This paper describes the fabrication of thin(<1 μm) single crystal SOS layers. This is achieved by the void free room temperature bonding of SOI substrates, such as SIMOX, to sapphire, and the resulting thinning of the SOI by a combination of precision grinding and chemical etching. For the research described in this paper, 100 mm in diameter SIMOX and 100 mm diameter virgin sapphire substrates were employed. The thickness of the sapphire substrates was 500 μm, and the implanted oxide in the SIMOX substrates was buried 0.16 μm below the silicon surface. In order to establish a void free bond between the SOI and sapphire substrates, a 20 nm silicon dioxide layer must first be grown on the silicon layer. This promotes the establishment of a strong bonding wave. Due to the thermal mismatch between silicon and sapphire, standard high temperature bond annealing is not possible. Initial bond anneal temperatures have to be restricted to below 250ϒC. Thinning of the silicon layer after bonding is achieved by a combination of precision grinding and chemical etching. In order for the bond interface to withstand the grinding process, annealing the room temperature bond to 200ϒC for 1hr is required. By employing precision grinding, SOS layers greater than 10 μm are readily obtained on the non standard sapphire substrate. The bond strength at the silicon-sapphire bond interface is not strong enough to resist force of chemical mechanical polishing, (CMP), therefore, chemical etching is required to thin the resulting silicon layer to a thickness less than 1 μm. Thinning the silicon layer allows the bond anneal temperature to increase. Grinding the SOI layer to below 20 μm, enables the bond interface to be further strengthened by annealing at 350ϒC. After this anneal the bond interface is able to withstand chemical etching, but not polishing. KOH/IPA etchant is used to remove the remaining silicon, stopping at the buried oxide layer. Etching is performed at a temperature of 80ϒC, giving a silicon etch rate of approximately 1 μm/min. Once the silicon etching process has been completed, the exposed oxide layer can be removed leaving a thin single crystal SOS layer. Annealing at 900ϒC can now be performed to further increase the bond strength for future processing.

9:40 AM, AA5

Wafer Bonding of 3"-Diameter GaP to AlGaInP-GaP Light-Emitting Diode Wafers: I-HSING TAN[1]; Dave A. Vanderwater[1]; Jen-Wu Huang[1]; Gloria A. Hofler[1]; Fred A. Kish[1]; Eugene I. Chen[1]; Tim D. Osentowski[1]; [1]Hewlett Packard, Optoelectronics Division MS-91ML, 370 W. Trimble Rd., San Jose, CA 95131 USA

The highest efficiency AlGaInP light-emitting diodes (LEDs) were commercially introduced in 1994 based upon a wafer-bonded transparent-substrate (TS) platform. These AlGaInP/GaP LEDs have been shown to exhibit luminous efficiencies exceeding many conventional lightning sources including typical 60 W tungsten source. Wafer bonding over 2"-Diameter AlGaInP LED wafers has previously been demonstrated. This talk will demonstrate the feasibility of scaling bonding to the 3" wafers and some of the unique challenges associated with this scaling. Wafer bonding over the entire 3" wafer is achieved while maintaining low-resistance electrical conduction and optical transparency at the bonding interfaces. The quality and uniformity of bonding were characterized via the scanning acoustic microscopy, scanning electron microscopy, transmission optical microscopy, full wafer mapping of the LED performance, and reliability stress tests. These high bonding yields facilitate the low-cost, high-volume fabrication of TS AlGaInP/GaP and will further enable these devices to compete with other lighting sources.

10:00 AM Break

10:20 AM, AA6

Crystal Ion Slicing of Single-Crystal Films of Lithium Niobate: MIGUEL LEVY[1]; R. M. Osgood[1]; R. Liu[2]; Eric Cross[2]; Atul Kumar[3]; Hassaram Bakhru[3]; [1]Columbia University, Dept. of Applied Physics, 500 West 120th Street, SEAS, Rm. 1336, New York, NY 10027 USA; [2]Pennsylvania State University, Materials Research Laboratory, 187 Materials Research Lab, University Park, PA 16802 USA; [3]State University of New York at Albany, Physics, 1400 Washington Avenue, Albany, N.Y. 12222 USA

Lithium niobate ($LiNbO_3$) is a technologically important ferroelectric material, possessing a large room-temperature electro-optic coefficient. It is the material of choice in the fabrication of optical modulators, interferometers, and switches for photonic circuit applications. But its use in integrated photonics is limited by the fact that single-crystal $LiNbO_3$ cannot be grown on semiconductor substrates, thus restricting its integration with lasers sources and other optical components. We report here the first fabrication of single-crystal $LiNbO_3$ films, using a technique previously reported by some of us for the epitaxial liftoff of magnetic garnets.[1] Deep ion-implantation is used to create a buried sacrificial layer in single-crystal bulk samples of $LiNbO_3$. Helium ions at 3.8 MeV of energy are implanted several microns below the top surface with little residual damage to the near-surface region. The damage generated by the implantation induces a large differential etch rate between the sacrificial (damage) layer and the rest of the crystal. Nine-micron-thick films are then detached from the bulk by etching in hydrofluoric acid for 24 hours. The film thickness agrees with transport-of-ions-in-matter (TRIM) calculations of the implantation profile. Capacitive measurements of the dielectric response show that the detached films have the same dielectric constant as the bulk single-crystal, in contrast to sputtered polycrystalline films. Poled single-crystal films obtained by crystal ion-slicing maintain their polarization, indicating that the ion implantation does not cause the film to break up into ferroelectric domains. Measurements of the pyroelectric effect were performed by the Chynoweth technique and showed a strong thermal response in the spontaneous polarization. This work was supported under MURI/DARPA contract #F49620-96-1-0111. 1. Epitaxial Liftoff of Thin Oxide Layers: Yttrium Iron Garnets onto GaAs, M. Levy, R.M. Osgood, Jr., A. Kumar and H. Bakhru, Appl. Phys. Lett. 71, 2617 (1997)

10:40 AM, AA7

Improvement in the Surface Preparation of GaAs-Based Compliant Substrates: C. ZHANG[1]; D. Lubyshev[1]; D. L. Miller[1]; T. N. Jackson[1]; T. S. Mayer[1]; [1]The Pennsylvania State University, Department of Electrical Engineering, Electronic Materials and Processing Research Laboratory, University Park, PA 16802 USA

Recently, the use of compliant substrates for the growth of lattice-mismatched materials such as InGaAs/GaAs, SiGe/Si, and InSb/GaAs has received considerable attention. A variety of techniques have been investigated to prepare thin (<1000 Å) compliant layers that are separated mechanically from a rigid host substrate. The most promising of these methods include direct twist bonding where uniformly spaced, weakly bonded areas permit the substrate to conform to the growing epitaxial layers. In addition intermediate layers of SiO_2, AlGaAs-oxide, and borosilicate glass that separate the compliant layer from the host substrate have also been considered. In each case, however, proper preparation of the compliant layer surface prior to growth is critical to the success of lattice-mismatched epitaxy on compliant substrates. In this work, we studied the surface morphology of 100 - 200 Å GaAs compliant layers that were attached to a GaAs mechanical host substrate by twist bonding directly to the host substrate. Following wafer fusion, the 200 - 300 Å GaAs complaint layer was revealed by etching chemically the topmost GaAs substrate, and stopping selectively on an $Al_xGa_{1-x}As$ etch stop layer. We investigated removing the $Al_xGa_{1-x}As$ (x = 0.7, 0.9) etch stop layers with HCl and dilute HF, and determined by AFM that the rms roughness of the resulting compliant layer is 20 and 10 Å, respectively. Initial AES results suggest that the roughness is due to the presence of excess arsenic or arsenic oxide that is not removed completely during the selective etch. To improve the surface morphology of the compliant layer following the selective $Al_xGa_{1-x}As$ removal, a three-cycle digital etch using H_2O_2 and HCl or NH_4OH was performed. Following the digital etch, the rms roughness of the compliant layers were reduced to approximately 2 Å for both $Al_xGa_{1-x}As$ selective etchants. Although the rms roughness of the compliant layers is only 2 Å, isolated peaks that were 15 - 20 Å tall were observed throughout the sample. In order to assess the quality of the complaint substrate, a lattice-matched GaAs p^+-n diode was grown on the compliant substrates and compared to identical devices grown on standard GaAs substrates. Comparable reverse dark I-V characteristics were measured on all samples, which demon-

strates the relatively high quality of the wafer-bonded compliant substrates. Finally, $In_{0.2}Ga_{0.8}As$ p^+-n diodes were also deposited on the compliant substrates and on standard GaAs substrates to determine the effect of the surface preparation on the growth of lattice-mismatched materials. In all cases, the rms roughness of the $In_{0.2}Ga_{0.8}As$ epitaxial layers on the complaint substrates were approximately 75 Å as compared to 180 Å for layers on the GaAs control substrate. Although the layers on the complaint substrates had a smoother surface morphology, the reverse dark current of these diodes were approximately an order of magnitude higher than those on the GaAs control substrate. This indicates that the surface morphology of the compliant substrate prior to growth dominates the device characteristics for lattice-mismatched layers. Additional $Al_xGa_{1-x}As$ and AlAs etch-stop layers are being investigated in conjunction with the digital etching technique to improve further the surface morphology of the compliant substrates prior to growth.

11:00 AM, AA8+

Lattice Engineering Using Lateral Oxidation of AlAs: An Approach to Generate Substrates With New Lattice Constants: PRASHANT CHAVARKAR[1]; Li-Jie Zhao[2]; Stacia Keller[1]; Sheila Mathis[2]; Alexis Black[1]; Evelyn Hu[1]; James S. Speck[2]; Umesh K. Mishra[1]; [1]University of California, Dept. of Electrical and Computer Engineering, Santa Barbara, CA 93106 USA; [2]University of California, Materials Department, Santa Barbara, CA 93106 USA

The ability to grow strained psuedomorphic layers on commercially available substrates has enabled advances in GaAs pHEMTs and reduced the threshold current density in GaAs/InGaAs lasers. However the limit in the amount of lattice mismatch and layer thickness which can be accommodated still precludes the availability of technologically important devices such as 1.3 μm lasers on GaAs substrates and dislocation free mid IR lasers. These devices will be enabled by generating new lattice constants on which pseudomorphic active regions can be grown. This work illustrates an approach to the problem and demonstrates the generation of high quality, dislocation-free In0.13Ga0.87As bulk layers on GaAs substrates. We demonstrate a novel approach which uses the process of lateral oxidation of Al-containing compounds. Though not fully characterized at this time we propose that the tensile stress created in adjacent layers by the process of lateral oxidation of AlAs causes the relaxation of the InGaAs template layers aided by the weak Al2O3/InGaAs interface. The epitaxial template consists of an In0.2Ga0.8As/AlAs/In0.2Ga0.8As/AlAs structure grown on a GaAs substrate by MBE. The In0.2Ga0.8As layers are grown at low temperature and hence are strained and dislocation free. The templates are then patterned into 100 μm x 100 μm mesas by photolithography and RIE. The mesas are laterally oxidized in steam. After oxidation the protective layers on top are removed and thick (5000 Å) In0.13Ga0.87As layers are regrown on these templates by MBE. This epilayer thickness is about 15 times the critical thickness of In0.13Ga0.87As on GaAs substrates. TEM Analysis of the epistructure showed no threading dislocations or slip planes in both the epitaxial template and the regrown InGaAs epilayer indicating good structural quality. The In composition as determined from X-ray analysis is 13%. Off-axis X-ray analysis indicates that the layers are 75-80 % relaxed. Low temperature (6 K) PL spectra of the epilayer exhibited a peak at 1.354 eV with a linewidth of 10 meV. This again corresponds to a Indium composition of 13%. The rms surface roughness as measured using AFM is 8 Å. These results suggest that lattice engineering through lateral oxidation is a promising technique to generate substrates with new lattice constants. Moreover this approach is scaleable to large substrate sizes with an appropriate grid structure. Also through the use of appropriate oxidizing layers thus concept can be implemented on a InP substrate to generate lattice constants between InP and InAs and on GaSb substrates to enable the growth of IR materials. This work is supported by AFOSR under the PRET program.

11:20 AM, AA9+

A Study of Compliant Substrates Using InP Twist Bonding: JAE-HYUN RYOU[1]; Joongseo Park[1]; Uttiya Chowdhury[1]; Russell D. Dupuis[1]; David T. Mathes[2]; Robert Hull[2]; [1]The University of Texas at Austin, Microelectronics Research Center, PRC/MER 1.606D-R9900, Austin, TX 78712-1100 USA; [2]University of Virginia, Department of Materials Science and Engineering, Thornton Hall, Charlottesville, VA 22903-2442 USA

Compliant substrate technologies have been investigated to overcome the limitation of epitaxial growth on lattice-matched substrates. For example, for the growth of InxGaxAs on InP substrates, the In alloy composition, x, should be x ~ 53% to achieve good quality epitaxial layers. In this work, the growth of strained InGaAs on InP-based compliant substrates using wafer twist-bonding have been studied. The materials of this study have been characterized by Nomarski optical microscopy, atomic-force microscopy (AFM), and scanning electron microscopy (SEM) for examination of the surface morphology. In addition, X-ray diffraction (XRD), transmission electron microscope (TEM), and photoluminescence (PL) have been employed to characterize the crystal quality of these heteroepitaxial layers. The results of the growth of various lattice-mismatched InGaAs heteroepitaxial films on InP-based compliant substrate and on standard InP substrate are described. The InP "substrate" wafers to be twist-bonded are prepared using the following process. First, an InGaAs etch-stop layer and ~5 nm thick InP "compliant layer" are grown on a (100) InP substrate using low pressure metalorganic chemical vapor deposition (LP-MOCVD). Next, bonding is made at various relative orientations of the two InP crystallographic surfaces (e.g., 0, 10, 45 degrees), between the thin InP layer on the top of the as-grown wafer and a second (100) InP "host" substrate, which acts as a mechanically supporting substrate of the thin InP "compliant layer". Van der Waals bonding at room temperature is performed followed by direct fusion bonding at 600°C under various pressures. After bonding, the InP "host" substrate and the InGaAs "etch-stop" layer on thin compliant InP layer are removed. Finally, an intentionally lattice-mismatched InGaAs layer is grown on compliant substrate. Growth is also done on standard (100) InP substrate to compare with compliant substrate. As of this time, we have successfully grown InGaAs with a mismatch of up to 2% In (rich), resulting in a heteroepitaxial layer which is compressively strained. Triple-axis XRD analysis of these films is used to create a reciprocal space map (RSM) for these layers in order to analyze the mosaic spread of lattice parameters in the InGaAs layers. Increased mosaic spread is related to increased dislocation density of the films. The RSM for the InGaAs/compliant substrate shows a smaller relaxed feature due to the strain accommodation of compliant substrate. Also, the XRD peak of mismatched InGaAs on the compliant substrate has a smaller mosaic spread than the "companion" InGaAs layer grown on standard substrate.

Friday AM, June 26, 1998

Session BB. Compound Semiconductor Oxides

Room: 011
Location: Olsson Hall

Session Chairs: Carol I. H. Ashby, Sandia National Laboratories, Albuquerque, NM 87185-0603 USA; James B. Ibbetson, University of California, ECE Dept., Santa Barbara, CA 93106 USA

8:20 AM, BB1+

Evaluation of the Thermally Grown Oxide on Gallium Nitride: S. D. WOLTER[1]; E. D. Readinger[1]; S. E. Mohney[1]; [1]The Pennsylvania State University, Materials Science and Engineering, 218 Steidle Building, University Park, PA 16802 USA

The thermally grown oxide on GaN has been studied to provide information concerning its stability in oxidizing environments and the potential of the native oxide for device applications. In dry air, oxide formation was observed using glancing incidence x-ray diffraction when the temperature of oxidation was greater than 900ϒC, and the oxide was identified as β-Ga_2O_3. The rate of oxidation at 900ϒC was found to be linear with respect to time for all times studied (5-45h), as determined by measuring the thickness of the oxide on cleaved cross-sections viewed in the scanning electron microscope. The surface of the oxide was rough and faceted. Very similar results were obtained when oxidation was performed in dry O_2. Wet oxidation was next performed to evaluate the influence of water vapor on the rate of oxide growth and to inspect for morphological differences in the oxide. The carrier gases O_2, N_2, and Ar were used in initial experiments. A more rapid rate of oxidation with O_2 as the carrier gas (compared to the other carrier gases and that of dry air) prompted us to examine wet oxidation in O_2 more carefully. Again the oxide was identified as β-Ga_2O_3,

but the oxides grown in wet O_2 were much smoother than those grown in dry air. The rate of oxide growth at 900ϒC was again linear with respect to time. Interestingly, atomic force microscopy performed on much thinner oxides, less than 20nm thick, revealed lower root mean square surface roughness values for oxidation in dry O_2 when compared to wet O_2; however, upon growing the oxides to approximately 400nm thick, the wet grown oxides were much smoother. X-ray photoelectron spectroscopy data strongly suggests a Stranski-Krastanov type growth mode for both wet and dry oxidation. Several monolayers of oxide first grow, followed by the formation of discrete crystallites on the initial oxide layer. The thickness of the oxide on GaN exposed to laboratory air at room temperature was estimated to be approximately 10Å, while that of the thermal oxide prior to the formation of discrete crystallites was approximately 45Å. Preliminary measurements of the electrical resistivity of thicker oxides (100nm) grown in wet O^2 revealed resistivities in the range of 10^{10} to 10^{12} Ω-cm, with typical breakdown voltages of 1 x 10^5 V/cm. The oxides grown in dry air yielded comparable resistivities. These results as well as those from ongoing electrical characterization studies will be discussed.

8:40 AM, BB2+

Effect of Stress on Lateral Oxidation Rates in AlAs And AlAsSb: PRASHANT CHAVARKAR[1]; Sheila Mathis[2]; James Champlain[1]; James S. Speck[2]; Umesh K. Mishra[1]; [1]University of California, Department of Electrical and Computer Engineering, Santa Barbara, CA 93106 USA; [2]University of California, Materials Department, Santa Barbara, CA 93106 USA

Oxidation of Al-containing compounds has been widely investigated in the recent past. We demonstrate for the first time that stress in the oxidizing layers itself affects the oxidation rates. Compressive stress in the oxidizing layers enhances the oxidation rates whereas tensile stress reduces the oxidation rates. Compressive stress was introduced in AlAs layers by addition of Sb. Growth of AlAs on partially relaxed $In_{0.2}Ga_{0.8}As$ layers resulted in tensile strained layers. 100 μm x 100 μm mesas were defined by photolithography and RIE. These mesas were laterally oxidized in steam at temperatures ranging from 350 to 425 ϒC. Addition of Sb to AlAs resulted in enhancement of oxidation rates. This effect is observed in the activation energy of oxidation rate which is 1.28 eV for AlAs, 1.00 eV for $AlAs_{0.97}Sb_{0.03}$ and 0.8796 eV for $AlAs_{0.95}Sb_{0.05}$. Though the presence of Sb results in higher oxidation rates, it is postulated that in AlA $s_{1-x}Sb_x$ ($x<0.05$) compressive stress plays the major role in increasing the oxidation rate. This is indeed the case as activation energy for oxidation of lattice-matched (strain-free) $AlAs_{0.56}Sb_{0.44}$ on InP is higher (1.12 eV) than the activation energy for $AlAs_{0.99}Sb_{0.01}$ (compressive strained) on GaAs (1.00 eV). On the other hand oxidation rate of AlAs reduces with the tensile stress. Reduction of oxidation rate can be observed in the activation energy for oxidation rate which increases from 1.28 eV to 1.465 eV for AlAs grown on 600 Å InGaAs, and to 1.888 eV for AlAs on 1000 Å InGaAs. The above effect can be explained in terms of strain at the oxidation front. There is tensile strain in the oxidizing layer in a localized region at the oxidation front. Less amount of energy is required to create tensile deformation in a compressively strained layer. On the other hand more energy is required to create tensile deformation in a tensile strained layer. This information is useful in designing oxide based device structures like VCSELS, HBTs and RTDs where the oxidizing AlAs layers are strained.

9:00 AM, BB3

Wet Oxidation of AlGaAs: Elemental Arsenic and Its Influence on the Oxidation Process: CAROL I.H. ASHBY[1]; Ray D. Twesten[2]; Kent D. Choquette[1]; David M. Follstaedt[1]; Kent M. Geib[1]; Olga Blum[1]; Hong Q. Hou[1]; [1]Sandia National Laboratories, Dept. 1314, MS 0603, PO Box 5800, Albuquerque, NM 87185-0603 USA; [2]Center for Microanalysis of Materials, University of Illinois, Urbana, IL 61801 USA

Wet oxidation of high-Al-content AlGaAs layers in vertical cavity surface emitting lasers (VCSELs) has produced devices with record low threshold currents and voltages and with wall-plug efficiencies greater than 50%. Wet oxidation of buried AlGaAs layers has also been employed to reduce the problems associated with substrate current leakage in GaAs-on-insulator (GOI) MESFETs. To continue improving device designs for even higher performance and to establish a truly manufacturable technology based on wet oxidation, it is important to understand how oxidation of one layer affects the electrical and chemical properties of adjacent layers. To first order, the oxidation rate is determined by the Al mole fraction. However, the production of large amounts of elemental As during the oxidation and its diffusion into adjacent regions can modify the electrical and chemical properties of these regions in ways that can impact device design, fabrication, and performance. The close proximity of a faster-oxidizing layer can produce a several-fold increase in oxidation rate for a layer of a given Al composition over the rate obtained with an isolated layer of the same composition. Injection of As interstitials into adjacent layers and the consequent development of additional defects, such as As antisite defects and group-III vacancies and interstitials, can alter the oxidation rate for nearby regions. Observed rate accelerations are consistent with the diffusion of As-generated defects from the fast-reaction layer to the slower-reaction layer. In addition to alteration of oxidation rates, the As-caused defects can alter electrical and optical properties of adjacent layers. A model based on the role of elemental As in such behavior as enhanced oxidation rates in close proximity to faster-oxidizing layers, dependence of oxidation rate on proximity of one of several oxidizing layers to the surface or substrate, asymmetry in the oxidation front profile of a given layer depending on position within the total structure, and effects of dielectric overlayers will be discussed. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

9:20 AM, BB4+

AlAs Oxidation Rate Dependence on the Adjacent Layer Composition: RYAN L. NAONE[1]; Larry A. Coldren[1]; [1]Univ. California at Santa Barbara, Materials Department, Santa Barbara, CA 93106 USA

The lateral oxidation rate of AlAs layers decreases dramatically for thinner layers along with a corresponding increase in the activation energy, Ea, associated with the reaction occurring at the oxidation front. These observations are consistent with a model based on the surface energy of the curvature seen at the oxide tip. Because of this curvature the Gibbs-Thomson effect gives an additional energy, ΔG, which is included in E_a. This model predicts that adding Al to the GaAs layers immediately adjacent to the AlAs oxidation layer will increase ΔG. Using a 25 nm AlAs layer cladded by AlGaAs layers of various compositions from 0% to 38% Al, we observe an increase in E_a with increasing Al composition, as predicted. However, as seen in the figure, the behavior of the overall oxidation rate as a function of barrier composition is complicated by the Arrhenius prefactor. Specifically, for temperatures above 410 ϒC the oxidation with higher Al content barriers oxidizes faster, despite the higher activation energy. Below this temperature the oxidation is slower for the higher Al content barriers.

9:40 AM, BB5+

Room Temperature Photoluminescence of Er-Implanted AlGaAs Native Oxides: LEIGANG KOU[1]; Douglas C. Hall[1]; [1]University of Notre Dame, Dept. of Electrical Engineering, 275 Fitzpatrick Hall, Notre Dame, IN 46556-5637 USA

Data are presented demonstrating continuous (cw), room-temperature (300 K) photoluminescence (PL) near 1530 nm from Er-implanted $Al_xGa_{1-x}As$ films ($x \oplus 0.8$) thermally oxidized at 500 ϒC in water vapor. A 10^{15} cm^{-2} implant dose of doubly-ionized Er at 80 KeV yields an implantation profile estimated using the Monte Carlo program TRIM'95 to have a range of 460 Å and a straggle of 180 Å, for a peak Er concentration of about 2.1 x10^{20} cm^{-3}. The ~1 μm thick $Al_xGa_{1-x}As$ films, implanted through a 200 Å GaAs cap layer, are later fully oxidized from the surface after the cap layer is removed. A large PL intensity increase (~20X for a native oxide of $Al_{0.8}Ga_{0.2}As$:Er) upon annealing for 1 h at 700 ϒC in an Ar + O_2 atmosphere is attributed to a reduction in the concentration of luminescence-quenching O-H compounds. Similar anneals in N_2 alone are not nearly as effective. Higher temperature annealing leads to an intensity decrease, consistent with a possible phase transformation of the oxide. Broad ⊕ 50 nm full-width at half-maximum (FWHM) PL spectra are consistent with an amorphous microstructure of the oxide host. These PL spectra are ~10X more intense and ~2X broader than the 27 nm FWHM spectra from unoxidized $Al_{0.8}Ga_{0.2}As$:Er annealed under the same conditions, but with a 1000 Å PECVD Si_3N_4 cap layer and in proximity to a GaAs wafer to protect against thermal decomposition. These data suggest that the native oxide is a more suitable host for optical activity from the rare earths than the unoxidized semiconductor. The fluorescence decay of the Er-doped native oxide shows double-exponential behavior with two lifetimes, 7 ms and 1.9 ms, with the faster decay characteristic of a cooperative upconversion mechanism associated with ion-ion interactions. The effects of varying the Al composition, implant dose, and annealing conditions are discussed. Further optimization may enable the monolithic integration of semiconductor pump lasers and Er-doped native oxides for wavelength-stable sources or planar waveguide amplifiers for photonic integrated circuits.

10:00 AM Break

10:20 AM, BB6

The Effect of a Non-Stoichiometric Buffer on the Oxidation and Electrical Properties Of GaAs-On-Insulator (GOI) Field-Effect Transistors: JAMES GALLOWAY CHAMPLAIN[1]; Primit Parikh[1]; James Ibbetson[1]; Umesh Mishra[1]; [1]University of California, Electrical and Computer Engineering, Santa Barbara, CA 93106 USA

Preliminary work on the effect of introducing a non-stoichiometric buffer layer underneath the $Al_xGa_{1-x}As$ (to be converted to Al_2O_3) layer in a GOI field-effect transistor (FET) structure has been performed. Several FET samples were grown by solid-source molecular beam epitaxy (MBE). In all samples a conventional undoped 2000 Å GaAs was grown at 580 ℃. Next, in some samples, a LT $Al_xGa_{1-x}As$ (x=0 to 0.7) buffer was grown at 270 ℃. The LT AlGaAs layer was annealed at 550 ℃ at the completion of its growth. Growth of the GOI FET structure continued for all samples with a 500 Å $Al_{0.98}Ga_{0.02}As$ (to be oxidized). For samples with a LT AlGaAs buffer, the growth temperature during the $Al_{0.98}Ga_{0.02}As$ layer was ramped from 550 ℃ to 600 ℃ to aid in smoothening the growth surface. For samples without a LT AlGaAs buffer, the growth temperature was ramped from 580 ℃ to 600 ℃. Following the growth of the $Al_{0.98}Ga_{0.02}As$ layer the growth temperature was returned to 580 ℃. Next, a 100 Å grade from $Al_{0.98}Ga_{0.02}As$ to $Al_{0.3}Ga_{0.7}As$ was grown, followed by a 100 Å $Al_{0.3}Ga_{0.7}As$ spacer layer, a 1000 Å n- (5 x 10^{17} /cm^3, Si) GaAs channel, and a 30 Å $Al_{0.7}Ga_{0.3}As$ etch stop layer. At this point the growth temperature was reduced to 470 ℃ for growth of the 10 Å GaAs/5 Å InAs, 10 period super-lattice and 50 Å InAs ohmic cap layer. Wet thermal oxidation was performed on all samples and it was found that the lateral oxidation rate of the insulator/buffer layer is greater for samples with a LT buffer layer as compared to samples with only the conventional GaAs buffer, and that the rate dramatically increases with increasing LT buffer layer aluminum percentage. Preliminary results from our electrical characterization show a highly desirable reduction in charge loss in the FET channel after oxidation with the introduction of a LT $Al_{0.3}Ga_{0.7}As$ buffer. FETs with a conventional GaAs buffer showed a 2.18 x 10^{12} /cm^2 depletion in the channel, whereas FETs with a LT $Al_{0.3}Ga_{0.7}As$ buffer showed only an 8.11 x 10^{11} /cm^2 depletion. Further characterization is underway at this time and will be presented in the future.

10:40 AM, BB7

Formation of Amorphous Al-Bearing Native-Oxide by Wet Oxidation with High Interface Quality Using a Thin GaP Barrier Layer: LI-JEN CHOU[1]; KUANG-CHIEN HSIEH[1]; David Wohlert[1]; Gregory Pickrell[1]; Keh-Yung Cheng[1]; [1]University of Illinois, Department of Electrical and Computer Engineering, 1406 W. Green St., Urbana, IL 61801 USA

Al-bearing native oxides formed by wet oxidation of crystalline AlGaAs have found great applications in light emitting devices but limited success for use as the gate oxide in a metal-oxide-semiconductor (MOS) structure. Microcrystallites formed in the native oxide, rough oxide-GaAs interface and the presence of As atoms near the interface which give rise to a high density of interface traps have been attributed to the limited progress. A new approach is proposed to address these issues. Amorphous (Ga,As) and (Al,As) compounds having an excess As about 50% higher than the crystalline GaAs have been deposited on GaAs, InP and GaP substrates by molecular beam epitaxy at low temperatures and wet-oxidized to form a truly amorphous native aluminum oxide layer as characterized by transmission electron microscopy (TEM). Auger electron spectroscopy (AES) profiles indicate a complete depletion of As in the oxide layer resulting from an easy escape of As through the porous amorphous oxide. In contrast, oxidation of the amorphous (Ga,As) compounds leads to the formation of GaAs microcrystallites on the order of 30Å through a solid state recrystallization mechanism which are embedded in an otherwise amorphous gallium oxide layer. Complete removal of As in the gallium oxide layer requires oxidation at higher temperatures. Extensive wet oxidation of the amorphous (Ga,As)/(Al,As) heterostructures on GaAs, however, results in an As loss near the surface of the underlying GaAs substrate as characterized by TEM and AES. Similar degradation is also observed near the surface of InP substrates. Improvement of the oxide-GaAs interface has been achieved by incorporating a thin GaP barrier layer of about two monolayers on the GaAs substrate prior to the deposition of amorphous (Al,As) compounds. Oxidation at 400 ℃ for 30 minutes yields a uniform aluminum oxide without noticeable damage to the underlying GaAs surface. High resolution TEM shows an interfacial roughness on the order of less than 15 Å, which is comparable to t he SiO_2/Si counterpart in a Si-based MOS structure. In addition, an enhancement of photoluminescence of more than three order of magnitude as compared to the as-grown counterpart without a GaP barrier indicates a great reduction in interface electronic traps. Having accomplished to reduce the interface trap density, to improve the interfacial roughness and to form an amorphous native oxide, this technique has a potential use in GaAs-based metal-oxide-semiconductor field-effect transistors.

11:00 AM, BB8

GaAs MOS Diodes Using Ultra-Thin $Ga_2O_3(Gd_2O_3)$ Oxide Films: T. S. LAY[1]; TSONG-SHENG LAY[2]; M. Hong[3]; C.T. Liu[1]; J. Kwo[1]; M. A. Marcus[1]; [1]Institute of Electro-Optical Engineering, National Sun Yat-Sen University, Kaohsiung 80424 Taiwan; [2]National Sun Yat-Sen University, Insititute of Electro-Optical Engineering, Kaohsiung, Taiwan 80424 Republic of China; [3]Bell Labs, Lucent Technology, 700 Mountain Ave, NJ, 07974-0363 USA

The recently discovery of an in-situ MBE-grown $Ga_2O_3(Gd_2O_3)$ film as the gate oxide has led to the first demonstration of enhancement mode GaAs MOSFETs [1]. For sub-micron GaAs device applications, the current leakage in the gate dielectric of reduced thickness has been an important issue. In this work, we address this aspect for the $Ga_2O_3(Gd_2O_3)$ thin films deposited on n-type GaAs and present I-V and C-V characteristics of the GaAs MOS structures as a function of the gate dielectric thickness, ranging from 16.6 nm to 7.7 nm. The as-deposited thin dielectric layer shows an excellent insulator performance: a gate leakage current density as low as 10^{-9} A/cm^2 at low gate bias up to 2.5 V. At higher bias, the direct tunneling current rises and the electrical breakdown field reaches as high as 11 MV/cm. Also, the C-V traces in the dark show a sharp accumulation-depletion transition, and an inversion layer formation. All the features are comparable to those of the state-of-art, ultra-thin SiO2 films in the SiO2/Si system [2]. We have also carried out high-resolution transmission electron microscopy (HRTEM) and X-ray reflectivity measurement to examine the microstructure and to determine the interfacial roughness. The samples show a sharp and uniform dielectric/GaAs interfacial transition with a roughness of ~ 0.24 nm. [1] F. Ren, et al., IEEE IEDM, p.943, 1996. [2] C.T. Liu, et al., IEEE IEDM, p.85, 1997.

11:20 AM, BB9+

Optical Properties of Native-Oxide Antireflection Coatings on GaAs: KEVIN J. KNOPP[1]; Richard P. Mirin[1]; Kris A. Bertness[1]; David H. Christensen[1]; Ron A. Synowicki[2]; [1]NIST, Optoelectronics Division, 325 Broadway, MS 815.04, Boulder, CO 80303 USA; [2]J.A. Woollam Company, Inc., 645 M St. Suite 102, Lincoln, NE 68508 USA

Wet thermally-oxidized AlGaAs has been used in light-emitting diodes and vertical-cavity surface-emitting lasers in which its insulating properties and low optical index provide current and optical-mode confinement. We have studied the application of these native oxide layers in both buried and surface layer geometries for use in single and multilayer antireflection coatings on GaAs. Additionally, we report the measured dispersion curves and the percent expansion/contraction for both oxidized stoichiometric and low-temperature grown (LTG) $Al_{0.98}Ga_{0.02}As$ as well as observed oxidation rates and selectivity. We have investigated native-oxide antireflection (NOAR) coatings made from a single λ/4 surface-oxide layer, from a λ/4 semiconductor layer paired with a λ/4 surface-oxide layer, and from two semiconductor and oxide layers of arbitrary thickness. A two-layer λ/4 surface-oxide / AlAs coating on GaAs theoretically exhibits a region of less than 1% reflectance over >350 nm with a minimum reflectance of <0.05%. Analysis of a modified Schuster diagram reveals, that in order to exactly match to equivalent "substrate" indices that are lower than GaAs, a buried oxide layer (rather than a surface oxide layer) is required. Further, removing the λ/4 thickness restraint on this two-layer coating and exploiting the continuously variable refractive index, the composition of the matching layer can be chosen for oxidation selectivity as the thickness of the layer becomes the variable parameter. We fabricated the NOAR coatings by wet-thermally oxidizing $Al_{0.98}Ga_{0.02}As$ in a 450°C furnace under a flow of nitrogen gas bubbled through deionized water at 75°C for 2-12 minutes. We have made single-layer coatings using both oxidized stoichiometric and LTG $Al_{0.98}Ga_{0.02}As$ that exhibit reflectance minima of 3.6% at 1000 nm and 8.3% at 1300 nm, respectively. The thickness and index of both coatings were characterized with a variable-angle spectroscopic ellipsometer at incidence angles of 65°, 70°, and 75° over the spectral range of 240-1700 nm. The refractive index of the oxides was modeled using a Cauchy dispersion function. The measured index of the oxidized stoichiometric sample at 1000 nm was 1.57. By comparing the oxide thickness measured by ellipsometry with fitted in-situ reflectance data, the oxide

film was thinner than the AlGaAs layer by about 1.4%. The index of the oxidized LTG sample at 1300 nm was 1.45. The oxide film is thicker than the AlGaAs layer by 30%. We have also fabricated a two-layer NOAR coating from a λ/4 surface-oxidized, stoichiometrically grown $Al_{0.98}Ga_{0.02}As$ and a matching λ/4 oxide-stop layer of $Al_{0.90}Ga_{0.10}As$. This coating displays less than 2% reflectance over >200 nm with a minimum reflectance of 1.35% at 1255 nm. We have demonstrated that NOAR coatings can rival the performance of conventional dielectric coatings while simplifying their manufacture. Through the use of both buried and surface oxide layers, a wide range of aperture sizes and device geometries can be accommodated. Detailed experimental and simulation results on surface and buried NOAR coatings and their application to emitters and detectors will be presented.

Friday AM, June 26, 1998

Session CC. Devices and Transport Properties in Nitrides

Room: 120
Location: Olsson Hall

Session Chairs: J. Schelzina, North Carolina State University, Raleigh, NC 27695-8202 USA; Ilesanmi Adesida, University of Illinois, ECE Department, Urbana-Champaign, IL 61801

8:20 AM, CC1

InGaN MQW Lasers Grown on SiC: KATHY DOVERSPIKE[1]; Gary E. Bulman[1]; Scott Sheppard[1]; Kevin Haberern[1]; H. K. Kong[1]; H. Dieringer[1]; Michelle Leonard[1]; John Edmond[1]; Y. K. Song[2]; M. Kuball[2]; Arto Nurmikko[2]; [1]Cree Research, 4600 Silicon Drive, Durham, NC 27703 USA; [2]Brown University, Center for Advanced Material Research, 182 Hope Street, Providence, RI 02912 USA

Currently, there are several groups, Nichia, Toshiba, Cree, Fujitsu, Sony, UCSB, Xerox, Hewlett Packard, and SDL who have reported lasing from GaN based structures. All of these groups with the exception of Cree and Fujitsu use sapphire as the substrate. Because of the high thermal conductivity of SiC compared to sapphire, and also the ability to easily form cleaved facets, improved performance may be expected for lasers grown on SiC. Although many groups have now reported lasing, only two groups have shown cw operation of GaN based lasers, Nichia and Cree Research. We observed cw operation on devices with a current density of 21-25kA/cm^2. We later improved the currently density to approximately 10^{-11} kA/cm2. However, these improvements in the threshold of laser devices grown at Cree did not result in longer cw lifetimes. In the present work, recent work and the most recent lifetimes will be presented as a result of optimization of the various layers. All of the three groups who are currently selling blue /or green InGaN based LEDs, Nichia, Toyoda, and Hewlett Packard, use sapphire as the substrate. Subsequently, there have been many reports in the literature of InGaN based structures on sapphire. On SiC, however, there have been relatively few reports on the growth of InGaN layers, especially higher composition In layers. Results of InGaN based MQW structures on SiC ranging from 15% to 55% will also be presented.

8:40 AM, CC2

CW Operation of InGaN/GaN/AlGaN-Based Laser Diodes Grown on GaN Substrates: SHUJI NAKAMURA[1]; Masayuki Senoh[1]; Shin-ichi Nagahama[1]; Toshio Matsushita[1]; [1]Nichia Chemical Industries Ltd., R&D Department, 491, Oka, Kaminaka, Anan, Tokushima 774 Japan

We previously reported InGaN multi-quantum-well (MQW)-structure laser diodes (LDs), which have AlGaN/GaN modulation-doped strained-layer superlattices (MD-SLSs), within the critical thickness range, as cladding layers instead of thick AlGaN layers in order to prevent cracking of the AlGaN layers. Epitaxially laterally overgrown GaN (ELOG) on sapphire was used to reduce the number of threading dislocations of the GaN epilayer. Using both the MD-SLSs and the ELOG substrates, LDs with an estimated lifetime of more than 10,000 hours were developed. In the structures, sapphire substrates were used. Using a sapphire substrate, it is difficult to obtain cleaved mirror facets which are used for the cavities of conventional LDs. Also, the thermal conductivity of the sapphire is relatively small in order to dissipate the heat generated by the LDs. Here, the LDs grown on GaN substrates which are easily cleaved and have a high thermal conductivity, are described. The ELOG on sapphire was used to reduce the number of threading dislocations originating from the interface of the GaN epilayer with the sapphire substrate. The GaN layer above the SiO_2 mask area surrounding the window and corresponding to the lateral overgrowth, was nearly free of the threading dislocations. A high density of threading dislocations were observed in the vicinity of GaN grown in the window regions. After 100-γm-thick GaN growth on the ELOG, the sapphire substrate was removed by polishing in order to obtain pure GaN substrate with a thickness of approximately 80 γm. InGaN MQW/GaN/AlGaN separate confinement heterostructure (SCH) LDs which structure was described in detail previously were grown on this pure GaN substrates. The thickness of the n-type AlGaN/GaN MD-SLS cladding layer was increased from 0.6 γm to 1.2 γm in order to reduce the penetration of the laser light to the 3-γm-thick n-type GaN and the GaN substrate, which causes extra multi-modes in the far-field patterns (FFP) by coupling with the laser waveguide. The area of the ridge-geometry LD was 3 γm x 550 γm. A mirror facet was formed by dry etching, as reported previously. High-reflection facet coatings (50 %) consisting of 2 pairs of quarter-wave TiO_2/SiO_2 dielectric multilayers were used to reduce the threshold current. The LDs showed a small thermal resistance of 30℃/W and a lifetime of longer than 780 hours at an output power of 3 mW under RT-CW operation despite a large threshold current density of 7 kA/cm^2. In contrast, the LDs with the same threshold current density grown on a sapphire substrate exhibited a high thermal resistance of 60℃/W and a short lifetime of 200 hours under room-temperature continuous-wave operation. The LD with a threshold current density of 5 kA/cm^2 grown on the GaN substrate demonstrated an estimated lifetime of more than 10,000 hours. At an output power of 7 mW, a single-mode emission was observed at a wavelength of 393.3 nm. When we cleaved the facets along <1-100> of the LDs grown on the GaN substrate, the cleaved mirror facets were obtained easily. The FFP of the LDs with the cleaved mirror facets was measured in the planes parallel and perpendicular to the junction. The FFP revealed a single mode emission without any interference effects which were observed in previous LDs due to a reflection of the laser beam by the remaining sapphire substrate. The beam full-width at half power (FWHP) level for the parallel and perpendicular FFP were 8℃ and 31℃, respectively. The aspect ratio was approximately 4.

9:00 AM, CC3

Gallium Nitride Based UV and Violet LEDs on Silicon: SUPRATIK GUHA[1]; Nestor A Bojarczuk[1]; Joseph M Karasinski[1]; [1]IBM T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, NY 10598 USA

There has always been an impetus to develop epitaxial compound semiconductor based optoelectronic devices on silicon-the most convenient substrate in microelectronics-for obvious technological advantages. One of the potential applications that a Si based III-N LED technology may bring about are applications for miniature full color displays where UV or violet LED arrays are coated with pixelated organic color convertors. Using molecular beam epitaxy, we have demonstrated the first gallium nitride light emitting diodes grown on silicon. Growths were carried out using a radio frequency source for nitrogen delivery and growth was initiated on Si<111> substrates by deposition of a thin 8 nm AlN layer. Following this, $Al_xGa_{1-x}N/GaN/Al_xGa_{1-x}N$ (0.05<x0.10) double heterostructures were grown epitaxially. Diodes were fabricated by deposition of a standard Ni/Au transparent p top contact, and the conducting n type Si substrate was used as a bottom contact for electron injection. The light emitting diodes electroluminesce in the ultraviolet (~ 360 nm) with a full width at half maxima of about 17 nm, and in the violet (~400-430 nm), corresponding to near band edge and deep level emission. Relative uv:violet intensities appear to depend upon the nitrogen to gallium flux ratio, with excess nitrogen enhancing the deep level emission. In forward bias, diodes start emitting light in the 4-7 volts range for different devices. The electroluminescence is bright enough that it can be observed under normal room illumination. Cross sectional transmission electron microscopy studies indicate a high density (~5x10^9 per square cm) of threading defects along with a large density of planar faults on the GaN(0001) close packed growth surface. Electron diffraction studies confirm a single crystal wurtzitic structure and a Si<111>//GaN<0001> and Si<011>//GaN<2,1,-1,0> orientational relation between substrate and epilayer. The electron microscopy studies also indicate that the AlN growth initiation layer is contiguous, uniform, and highly defective with a large number of defects thread-

ing across this layer. These defects possibly act as leakage paths, thus enabling electron injection from the Si substrate. A potential drawback for growth on Si substrates is cracking due to a thermal expansion coefficient mismatch that results in a tensile stress being impressed upon the III-N layers on cooling. Prospects for molecular beam epitaxy with respect to growth on silicon substrates, and its basic advantages and limitations, will be discussed.

9:20 AM, CC4+

Electrical Properties of P-N Junctions on Lateral Epitaxially Overgrown GaN: PETER KOZODOY[1]; James P. Ibbetson[1]; Hugues Marchand[1]; Paul Fini[2]; Stacia Keller[1]; James S. Speck[2]; Steven P. DenBaars[2]; Umesh K. Mishra[1]; [1]University of California, ECE Dept., Santa Barbara, CA 93106 USA; [2]University of California, Materials Dept., Santa Barbara, CA 93106 USA

Lateral Epitaxial Overgrowth (LEO) of GaN has attracted a great deal of attention as a technique to reduce the high threading dislocation density associated with GaN growth on mismatched substrates. For growth on sapphire, LEO GaN has been shown to reduce the threading dislocation density from 10^9 cm^{-3} to below 10^5 cm^{-3}. This reduction in dislocation density is expected to improve device performance and facilitate investigation of the fundamental properties of GaN films. In this work, the electrical impact of threading dislocations is examined through the characterization of p-n junctions. A GaN wafer was prepared by MOCVD using lateral overgrowth on a SiO_2 mask; the wafer featured both overgrown regions with a very low threading dislocation density and window regions where the GaN had grown vertically through the mask and retained the high dislocation density (approximately 5 x 10^8 cm^{-3}) associated with growth on sapphire. After the LEO GaN growth, the wafer was returned to the MOCVD reactor for further growth of a p-n junction structure, so that the p-n junction layers were grown both on the LEO GaN and on the standard dislocated GaN. Diode structures were fabricated on both regions of the wafer and their electrical characteristics have been compared. The forward-bias characteristics of the devices are similar and are dominated by the p-contact. However, the reverse bias current through the diode on LEO GaN is orders of magnitude lower than on dislocated GaN, indicating that the latter is dominated by leakage through levels associated with the dislocations. Typical values for the leakage current at a reverse bias of 20 V were 2 x 10^{-4} A cm^{-2} on dislocated GaN, while the current for p-n junctions on LEO GaN were below the measurement limit of 2 x 10^{-7} A cm^{-2}. The diodes on LEO GaN do exhibit some leakage current at higher reverse bias; this conduction is attributed to either point defects or side-wall effects. We have investigated this leakage current as a function of temperature in order to study the factors limiting device performance in the absence of threading dislocations. From this analysis we extract the energy level of a trap, possibly associated with a point defect, which we believe is responsible for the remaining reverse-bias leakage in these low-dislocation density devices.

9:40 AM, CC5

Breakdown Mechanisms in Al(GaN) Based Photodetectors: MATTHEW JUSTIN SCHURMAN[1]; Ian Ferguson[1]; [1]EMCORE Corporation, 294 Elizabeth Ave, Somerset, NJ 08873 USA

(Al)GaN based photodetectors both interdigital metal-semiconductor-metal and p-i-n photodetectors have been successfully grown and fabricated on sapphire substrates. However, at high bias voltages, avalanche breakdown appears to be present since a constant breakdown field of >10^5 V/cm was obtained. A negative temperature coefficient for the breakdown voltage was observed indicating that field assisted tunneling is occurring. The avalanche breakdown appears to be nucleated at non-uniform field distribution within the device and is observed as microplasmas. It will be shown that premature breakdown has been minimized by reducing the structural defect density in the (Al)GaN with a corresponding reduction in dark currents. Continuing reductions in defect densities will be key in producing viable avalanche devices. Keywords: III-Nitrides, UV Photodetector, tunneling, avalanche breakdown

10:00 AM Break

10:20 AM, CC6

GaN Growth on 6H-SiC for Heterojunction Device Applications: JOHN T. TORVIK[1]; Moeljanto W. Leksono[1]; Christian Heinlein[2]; Jacques I. Pankove[1]; [1]Astralux Inc., 2500 Central Ave., Boulder, CO 80301 USA; [2]NTNU, Dept. of Physical Electronics, Trondheim, N 7034 Norway

GaN and 6H-SiC hold great promise for high temperature and high power electronic devices. Heterojunctions have been widely used to enhance performance in devices such as transistors. To form a GaN/SiC heterojunction, especially for minority carrier flow, great care has to be taken to reduce recombination centers. We therefore investigated the MOCVD growth of GaN on Si-face n- and p-type 6H-SiC. We studied: 1) selective GaN growth, 2) the effect of flowing ammonia (NH_3) at 1050°C on the SiC, 3) the conductivity type and concentration of the SiC substrate, and 4) GaN growth temperature. Heterojunction diodes made from direct and selective GaN growth were compared. The surface morphology of the GaN and forward diode characteristics were similar, but the reverse leakage current was two orders of magnitude lower in the selectively grown diodes that require no etching during fabrication. The effect of flowing NH_3 on the SiC substrate (nitridation) during growth was investigated. The concern was the H or N might react with or diffuse into the SiC forming Si_3N_4, or that C, Si or Al might diffuse from the SiC into the GaN. AFM measurements revealed that the SiC substrates (n and p) became smoother after the NH_3 treatment possibly due to a combination of nitridation and etching. The rms surface roughness was reduced from 1.52 nm to 1.17 nm and 2.33 nm to 1.31 nm for the p- and n-type SiC, respectively. SIMS measurements revealed no excess H, O, or N in the nitrided SiC, but exposed a tail of Al in the GaN due to out-diffusion from the p-SiC. Further evidence for a reaction at the GaN/SiC growth interface was uncovered when "recycling" a wafer used for selective growth. The GaN and SiO_2 were etched in boiling phosphoric acid and HF and the substrate was re-oxidized. The patterns where the GaN had grown reappeared as the oxide grew thinner there compared to the surrounding areas. Electrical characterization was performed on Cr/SiC (n~p~$10^{18}$$cm^{-3}$) Schottky diodes. Both the I-V and $1/C^2$-V traces revealed evidence for an increased potential barrier in the nitrided samples that can be explained by a interfacial monolayer of Si_3N_4. The effect of the SiC substrate conductivity type and concentration (10^{16}<n and p<10^{18} cm^{-3}) on the heterojunction diode characteristics was studied. The growth temperature was reduced from 1050°C to 950°C and 850°C to suppress the Al diffusion. The three N-n junctions exhibited similar $1/C^2$-V traces indicating little change in the doping as expected from the SIMS data. However, the slopes for the N-p heterojunctions indicate that the effective doping in the junction increases as the growth temperature increases. The I-V characteristics and implications of the surface reactions will be discussed.

10:40 AM, CC7

Capacitance-Voltage Characteristics of Strained AlGaN/GaN Heterostructures: Evidence For Graded Al Composition at Heterointerface: ALEXEI D. BYKOVSKI[1]; Remis Gaska[2]; J. W. Yang[2]; Michael S. Shur[3]; [1]University of Virginia, Dept. of Electrical Engineering, Thornton Hall, Charlottesville, VA 22903 USA; [2]APA Optics, Inc., 2950 N. E. 84th Lane, Blaine, MN 55449 USA; [3]Rensselaer Polytechnic Institute, CIEEM and Department of ECSE, CII 9015, 110 8-th Street, Troy, NY 12180-3590 USA

We report on the experimental and theoretical studies of the capacitance-voltage (C-V) characteristics of strained $Al_{0.25}Ga_{0.75}N$-GaN heterostructures grown on sapphire with the AlGaN barrier layer thickness varying from 10 nm to 100 nm. The measured C-V characteristics provided the strong experimental evidence that the piezoelectric effect causes an increase in the sheet electron concentration in heterostructures with $Al_{0.25}Ga_{0.75}N$ thickness up to 60 nm. The strain-induced electric field changes the charge distribution in the heterostructures. This, in turn, causes the shift of the CV characteristics with respect to their unstrained positions while preserving their general shape. The magnitude of the shift depends on the strain and the strained layer thickness. The direction of the shift (to a more negative or to a more positive voltage) is determined by the crystal orientation. Therefore, the magnitude of strain can be extracted from the comparison between the calculated and measured C-V characteristics. We calculated the charge distribution in our structures and the C-V characteristics by solving the Poisson equation with the boundary conditions accounting for the piezoelectric effect and the doping in GaN and $Al_{0.25}Ga_{0.75}N$. The analysis shows that the structures with the barrier layer thickness up to 20 nm thick are unrelaxed (i. e. strained). The relaxation increases gradually with the AlGaN thickness, and the structure with a 100-nm thick barrier layer is fully relaxed. The conventional theory of strain relaxation for abrupt interfaces yields the critical thickness of unrelaxed $Al_{0.25}Ga_{0.75}N$ barrier at least 1.5 times smaller than the value extracted from our C-V measurements. We attribute this difference to a gradual change in the Al mole fraction near the AlGaN-GaN heterointerface over approximately 5-6 nm.

11:00 AM, CC8

Electron Transport in Doped Channel AlGaN-GaN Heterostructures: Evidence of Transition Between 2D and 3D Electronic States: R. GASKA[1]; J. W. Yang[1]; M. S. Shur[2]; A. O. Orlov[3]; G. L. Snider[3]; [1]APA Optics, 2950 NE 84th Lane, Blaine, MN 55449 USA.; [2]Rensselaer Polytechnic Institute, CIEEM and Department of ECSE, CII 9015, 110 8th Street, Troy, NY 12180-3590 USA; [3]University of Notre Dame, Department of Electrical Engineering, Notre Dame, IN 46556 USA

Doped Channel AlGaN/GaN Heterostructure Field Effect Transistors have exhibited excellent characteristics. These devices demonstrated record values of the sheet carrier density (exceeding $4x10^{13}$ cm^{-2}), high electron mobilities at room and cryogenic temperatures (over 2,000 cm^2/V-s and 10,000 cm^2/V-s, respectively), high transconductance values (over 200 mS/mm at room temperature), large current carrying capabilities (up to 1.7 A/mm), and promising microwave performance (with the maximum frequency of operation over 100 GHz and the cutoff frequency-gate length product up to 18.9 GHz-micron). Understanding of the electron transport in doped heterostructures is crucial for further optimization of these devices. In this paper, we report on experimental and theoretical studies of the electron mobility in modulation doped AlGaN-GaN heterostructures grown on sapphire and 6H-SiC substrates. The calculated band diagrams of the doped channel $Al_{0.2}Ga_{0.8}N$-GaN heterostructures and the computed dependencies of the Fermi level on the sheet carrier concentration of the two-dimensional electron gas show that the potential well in the GaN near the heterointerface can contain up to between $1x10^{13}$ cm^{-2} and $1.5x10^{13}$ cm^{-2} electrons. At higher electron densities, electrons occupy three-dimensional states in the doped channel near the GaN-AlGaN heterointerface. This model can explain our experimental data on: (i) the decrease of room temperature electron Hall mobility with the channel doping. The mobility in $Al_{0.2}Ga_{0.8}N$-GaN heterostructures grown on sapphire and conducting 6H-SiC substrates decreases from 1,200 cm^2/Vs (on sapphire) and 2,000 cm^2/Vs (on 6H-SiC) at electron sheet density $n_s = 10^{13}$ cm^{-2}, to approximately 700-800 cm^2/Vs at $n_s > 3x10^{13}$ cm^{-2} for both types of the substrates; (ii) the non-monotonous electron mobility dependence on the gate bias in the "gated" Hall slab at temperature T = 4.2 K. The measured Hall mobility at 4.2 K first increases with the gate bias (from approximately 7,000 cm^2/V-s at V_g = - 4 V up to the record value of 11,000 cm^2/V-s at V_g = -0.5 V) and then decreases with a further increase in V_g down to 9,500 cm^2/V-s at V_g = 1.5 V). With an increase in the gate bias from - 4 V to 1.5 V, the sheet electron carrier concentration increases from approximately $3.5x10^{12}$ cm^{-2} to $1.1x10^{13}$ cm^{-2} at the gate bias V_g = 1.5 V. At the gate bias -0.5 V, which corresponds to the maximum Hall mobility, the electron sheet concentration is $8x10^{12}$ cm^{-2} and is close to the maximum n_s estimated for the 2D channel near $Al_{0.2}Ga_{0.8}N$-GaN heterointerface. These results are important for choosing the optimum doping in AlGaN-GaN Doped Channel Heterostructure FETs, which should be dependent on the gate length.

11:20 AM, CC9

Scaling of GaN/AlGaN MODFETs Grown by RF-Assisted GSMBE: CHANH NGUYEN[1]; Nguyen X. Nguyen[1]; David Grider[1]; [1]HRL Laboratories, MS RL61, 3011 Malibu Canyon Rd., Malibu, CA 90265-4799 USA

Electronic applications of group-III nitride materials have attracted much attention due to their favorable intrinsic properties, particularly for microwave power devices. However, because of the unavailability of bulk GaN substrates, heteroepitaxy has remained a critical issue in the development of GaN/AlGaN FETs. Furthermore, in order for GaN-based FETs to become useful in practical applications, devices have to be scaled to larger gate peripheries. Successful scaling of the device depends both on the uniformity of the epitaxial films and on the wafer to wafer reproducibility. We have demonstrated electronic device-quality materials grown directly on sapphire by rf-assisted MBE. Optimizing the growth condition, we have obtained GaN/AlGaN MODFETs with f_T of 28 GHz and f_{max} of 40 GHz. High uniformity in terms of both material and device characteristics has been achieved; less than 5% variation is observed across two-inch wafers. GaN/AlGaN MODFETs with 1.0 mm gate periphery have been successfully fabricated in this work using MBE grown materials. Device characteristics of these scaled GaN/AlGaN MODFETs have been investigated systematically as a function of the gate width from 200 μm to 1.0 mm. These devices are demonstrated to be readily scalable to 1.0 mm with a maximum drain current density of 700 mA/mm. Deviation from the linear dependence of current on gate periphery was observed, presumably due to self heating. Using a thick Au plated heat spreader, which also serves as the source interconnect, we obtained an improvement of about 22% in I_{max}. The general characteristics of these devices were preserved throughout the scaling range. Our results indicate that rf-assisted MBE can offer a viable solution to the problem of scaling GaN-based electronic devices to the level of practical interest.

Friday AM, June 26, 1998

Session DD. Non-Destructive Testing and In-Situ Monitoring/Control

Room: 005
Location: Olsson Hall

Session Chairs: Mark Goorsky, UCLA, Department of Materials Science and Engineering, Los Angeles, CA 90095 USA; Fred Pollak, Brooklyn College of CUNY, Physics Department, Brooklyn, NY 11210 USA

8:20 AM, DD1*Invited

Time Resolved Carrier Kinetics in Semiconductor Nanostructures: Fundamental Principles And New Results: STEPHEN E. RALPH[1]; Shriganesh S. Prabhu[1]; Brian R. Washburn[1]; Yue Chen[1]; Paul W. Juodawlkis[2]; Carl M. Verber[2]; David T. McInturff[3]; [1]Emory University, Department of Physics, 1510, Clifton Road (NE), Atlanta, GA 30322-2430 USA; [2]Georgia Institute of Technology, School of Electrical and Computer Engineering, 777, Atlantic Drive, Atlanta, GA 30332-0250 USA; [3]Purdue University, School of Electrical and Computer Engineering and the MRSEC for Technology Enabling Heterostructure Materials, 1285, Electrical Engineering Building, West Lafayette, IN 47907-1285 USA

The femtosecond temporal dynamics of optical and electronic phenomena in semiconductors reveals a wealth of information on the fundamental aspects of defects, transport and nonlinear optical phenomena. Frequently, these observations have clear implications for device performance. This paper provides a critical review of the various ultrafast optical techniques used to characterize semiconductors including the recently developed technique of terahertz spectroscopy. The importance of using multiple techniques and correlating these observations with additional static results is established. Additionally, the unique interaction of the terahertz field is shown and used to unambiguously identify carrier lifetimes in complex materials. Time domain studies have been dramatically impacted by the availability of tunable femtosecond-duration laser sources. In this regime, carrier dynamics are in a highly non-equilibrium condition and the relaxation dynamics are governed by many mechanisms, including carrier-carrier scattering, intervalley scattering, capture by quantum potentials, carrier cooling, and carrier-phonon scattering. Furthermore, some material systems may posses additional mechanisms which compete with these more common effects. For example, the defect states associated with low temperature growth (LTG) materials may yield subpicosecond carrier trapping times or may separately influence the momentum scattering rates. In this ultrafast regime, and certainly with these unique materials, the more traditional transient techniques including time resolved photoluminescence and transient absorption spectroscopy are often not able to uniquely characterize the free particle kinetics. In this paper, we will identify the different interaction mechanisms of each of these techniques within the framework of characterizing and understanding the carrier kinetics of standard temperature grown and LTG multiple quantum wells. We describe the various spectroscopic interactions in terms of the energy difference between the states involved, the dependence of the observable on the carrier distribution function and the carrier densities needed to perform the measurement. Ideally, one would like to determine the electron and hole occupation functions with arbitrary temporal resolution, however these spectroscopies are sensitive to products or sums of these functions. Furthermore, effects related to photoinduced absorption and high carrier densities prohibit the determination of these electron and hole occupation functions. Our investigation of low-temperature-grown materials, including GaAs and Be-doped $In_{0.53}G_{a0.47}As/In_{0.52}Al_{0.48}As$ multiple quantum wells exemplifies these difficulties. The goal of our characterization efforts is to provide useful information to the materials scientist so that we are able to understand the fundamental nature of defects and thereby control the carrier lifetime without detrimentally impacting the desirable linear and nonlinear

optical properties. The primary method of achieving this is through the controlled introduction of mid-gap defects states via low temperature growth. Using both wavelength-dependent time-resolved nonlinear bandedge absorption spectroscopy and far infrared terahertz spectroscopy we unambiguously discriminate between recombination and trapping events and thereby determine the carrier lifetime and mobility. We correlate the far infrared response, the transient bandedge response and Hall data to explain the apparent discrepancies with previous measurements. The role of compensation and the need to invoke separate recombination and trapping mechanisms is discussed.

9:00 AM, DD2

Time-Resolved Spectroscopy of Wide Band Gap Materials: FREDERICK H. LONG[1]; Milan Pophristic[1]; Chuong Tran[2]; Robert Karlicek[2]; Z. C. Feng[2]; Ian Ferguson[2]; [1]Rutgers University, Chemistry, 610 Taylor Road, Piscataway, NJ 08854-8087 USA; [2]EMCORE Corp., 394 Elizabeth Ave., Somerset, NJ 08873 USA

We have used picosecond time-resolved photoluminescence (PL) and femtosecond transient absorption to investigate films and multiple quantum wells (MQWs) of InGaN at room temperature. The film was 300 Å thick and both the film and the MQWs contained $In_xGa_{1-x}N$ with x=22%. A pump pulse at 400 nm (3.09 eV), originating from a ti-sapphire laser, was used to produce the PL. In both the MQWs and the film the PL lifetime increased with laser fluence. This effect is attributed to the saturation of recombination centers at high laser powers. With high laser powers, an average emission lifetime of 600 ps was observed in the film and emission lifetimes greater than 2 ns were observed in some MQWs. At laser fluences greater than $3x10^{13}$ cm^{-2}, the lifetime began to slowly decrease. In both the films and MQWs the emission lifetime became much shorter at shorter emission wavelengths. The dramatic change in the observed emission lifetime with wavelength is attributed to an increase in the density of states at higher energies and a subsequent increase in the decay rate. In many cases, the PL decays were clearly not single-exponential. A quadratic dependence of laser fluence on the PL signal was observed in the film. This is consistent with the PL originating from the bimolecular recombination of carriers. In contrast, in some MQWs, the PL signal varied linearly with laser fluence. This behavior is consistent with excitons. These two observations suggest that the nature of the excited state in $In_xGa_{1-x}N$ can vary depending on processing and dimensionality effects. In the MQWs, but not the $In_xGa_{1-x}N$ film, the PL spectra was observed to shift to higher energies with increasing fluence. A shift as large as 10 nm was observed. This change in the PL spectra was attributed to band filling. We will also present time-resolved measurements of yellow emission from 6H- and 4H-SiC at room temperature. Yellow emission, centered at about 570 nm, is quenched at the nitrogen concentrations greater than $2x10^{18}$ cm^{-3}. This emission is the subject of further investigation.

9:20 AM, DD3

Room Temperature Photoluminescence and Polarized Photoreflectance Characterization Of A Double-Side Doped GaAlAs/InGaAs/GaAs High Electron Mobility Transistor Structure Including the Influence of Strain Relaxation: F. H. POLLAK[1]; Y. S. Huang[1]; W. D. Sun[1]; L. Malikova[1]; I. Ferguson[2]; Z. C. Feng[2]; H. Hou[3]; [1]Brooklyn College of CUNY, Physics Department and New York State Center for Advanced Technology in Ultrafast Photonic Materials and Applications, Brooklyn, NY 11210 USA; [2]EMCORE Corporation, 394 Elizabeth Ave., Somerset, NJ 09973 USA; [3]Sandia National Laboratory, Albuquerque, NM 87185 USA

Using photoluminescence (PL) and photoreflectance (PR) at 300K we have characterized the properties of a double-side delta-doped ($1.7x10^{18}$ cm^{-3}) $Ga_{1-y}Al_yAs/In_xGa_{1-x}As/GaAs$ high electron mobility transistor structure fabricated by OMCVD, including the effects of strain relaxation in the channel. The nominal values of x, y and well width (L_w) were 0.2, 0.2 and 130Å, respectively. This sample was grown in the process of optimizing the device parameters. The techniques of PL and PR are very useful in evaluating the characteristics of the structure. In order to detect the anisotropic strain of the misfit dislocations related to strain relaxation, the PR measurements were performed for incident light polarized along [110] and [1-10]. The PL data produced the energies of the 1C-1H, 2C-2H and 2C-3H features from the InGaAs single quantum well (SQW). The notation mC-nH denotes a transition from the mth conduction band to nth valence band state of heavy-hole character. The PR spectrum contained signals from the InGaAs SQW in addition to the GaAlAs top layer and GaAs regions of the sample. From a detailed lineshape fit to the InGaAs data we were able to evaluate the two-dimensional electron gas density (2DEG) of $1.7x\ 10^{12}$ cm^{-2} in addition to the energies of the 2C-2H and 3C-3H transitions. The position of the GaAlAs peak corresponded to y = 0. 17. In such a double-side doped structure there is almost no electric field in the InGaAs channel, as opposed to single-side doped structures. Therefore there is no substantial quantum confined Stark effect and hence the "symmetry-allowed" m=n transitions will be the dominant features. We have performed a self-consistent Poisson's-Schroedinger's calculation of the 2DEG ($1.7x\ 10^{12}$ cm^{-2}) and the energy positions of the various transitions in the InGaAs SQW. While the calculated 2DEG was in good agreement with that determine from the PR lineshape fit it was not possible to account for the energies of the SQW features based on a pseudomorphic InGaAs channel with x = 0.2. Good agreement between theory and experiment could be achieved if we assumed either (a) a pseudomorphic structure with x = 0.24 or (b) a partially relaxed channel with x = 0.2. Evidence for the latter situation was provided by the observed anisotropy in the InGaAs PR signal for light polarized along [110] and [1-10] , an effect which we attribute to the anisotropic strain of the misfit dislocations associated with strain relaxation.

9:40 AM, DD4

Anisotropic Quantitative Mobility Spectrum Analysis (QMSA) Of Hall Properties in Silicon And Other Multivalley Semiconductors: IGOR VURGAFTMAN[1]; Jerry R. Meyer[1]; Craig A. Hoffman[1]; Jarek Antoszewski[2]; Lorenzo Faraone[2]; J. R. Lindemuth[3]; [1]Naval Research Laboratory, Optical Sciences Division, Code 5613, 4555 Overlook Ave SW, Washington, DC 20375 USA; [2]University of Western Australia, Dept. of Electrical and Electronic Engineering, Nedlands, WA 6907 Australia; [3]LakeShore Cryotronics, Inc., 575 McCorkle Blvd., Westerville, OH 43082

The quantitative mobility spectrum analysis (QMSA) is an advanced computer-automated technique for treating magnetic-field-dependent Hall measurements. QMSA is ideal for in-situ device characterization, since it maximizes the information attainable from a given data set, displays results in an easily interpreted "spectral" form, and can simultaneously derive densities and mobilities for multiple carrier species (e.g., both electrons in the n layers and holes in the p layers of HBTs). A number of important improvements to QMSA have recently been achieved, resulting in (1) much lower errors in fitting the experimental field dependences; (2) the natural emergence of low-mobility carrier species from the basic iteration procedure (previous approaches either ignored low-mobility carriers or resorted to extrapolating the data to magnetic fields far exceeding the maximum experimental value); (3) much more reliable preservation of spectral "linewidth" information related to the thermal or nonuniformity broadening of mobility peaks; and (4) minimization of "ghost" peaks and other unphysical features that can distort the derived carrier concentrations. The improved QMSA has been extensively tested using both synthetic data and actual measurements on a wide variety of semiconductor systems and heterostructures. Here our focus will be on a generalization of the algorithm that allows QMSA to accurately treat carriers in anisotropic X and L valleys. It will be shown that the assumption of isotropic conduction produces unreliable results for silicon and other multivalley semiconductors owing to the incorrect expressions for the fitted conductivity tensor components. On the other hand, proper inclusion of the anisotropy leads to an accurate determination not only of the net concentration and mobility, but also of the thermally induced "mobility broadening", which contributes to the Hall factor. We have used this analysis to extract the temperature-dependent Hall factor for NTD and ion-implanted silicon from the field-dependent magnetotransport data alone. The results are in good agreement with the values determined by other methods. As another example of the broad capabilities of the technique, we have also used the anisotropic QMSA formalism to simultaneously determine both L-valley electron and T-valley hole mobilities in Bi and BiSb thin films and quantum wells. These were then used to formulate an accurate model for the thermoelectric properties of the bismuth-based materials. The presented characteristics of the generalized QMSA make it broadly applicable to the characterization of anisotropic conduction in a wide variety of electronic devices based on such multivalley semiconductors as Si-Ge, SiC, AlAs, and the lead salts.

10:00 AM, DD5

A Technique for Determination of Free Carrier Concentration Profiles in Backgated Heterostructures: E. B. COHEN[1]; D. B. Janes[1]; K. J. Webb[1]; M. R. Melloch[1]; [1]Purdue University, School of Electrical and Computer Engineering, NSF MRSEC on Technology Enabling Heterostructure Materials, West Lafayette, IN 47907-1285 USA

Determination of the free carrier concentration of each layer in a heterostructure is basic to heterostructure device development. Standard C-V techniques are poorly suited to structures containing unknown deep donor concentrations, particularly in structures where deep donors are present near the top heterostructure layers, e.g. in GaAs/AlGaAs HEMTs. In such cases, the filling and emptying of the deep levels introduce an additional unknown charge density that complicates extraction of the true free carrier density as a function of depth using the standard C-V approach. As a result, systematic errors in the calculated concentration versus depth profiles are introduced. Furthermore, the presence of multiple intended conduction channels presents additional complications in extraction of the true density profile. We present a method of measuring free carrier concentrations in single- and multi-layer heterostructures as a function of gate bias. The particular heterostructure that was studied had a 2DEG above a low mobility channel, both of which shared the same source contact. The realization of a real space transfer velocity modulated transistor was the motivation behind this heterostructure [1,2]. However, the profiling approach we devised can be used wherever more than one channel, whether intentional or parasitic, exists. Consider the parasitic MESFET formed in the wide bandgap material between a top gate and a 2DEG channel, which occurred in our dual-channel device and also frequently appears in single channel HEMTs. In order to reduce the effects of deep levels between the top gate and the channel layers that induce the parasitic MESFET, we used a technique that extends the standard parallel plate depletion, C-V method by incorporating a second, bottom gate into the test structure. The two gates are located opposite one another, with the active layers sandwiched between them, the bottom gate consists of a doped semiconductor layer and the system is located on a semi-insulating substrate. In our approach, the top gate is held at a fixed potential, relative to the source, while the bottom gate is swept in order to deplete the heterostructure, and the capacitance is measured as a function of back gate bias. The electron concentration profile is computed using a parallel plate approximation. Next, the top gate potential is stepped and another sweep is performed. By integrating over the thickness of each layer, the carrier concentration profiles of each layer can be determined as functions of both the top gate and bottom gate potentials, with respect to the channel source reference. Since the top gate potential is held constant during each set of capacitance measurements, the uncertainties due to the action of deep levels between the top gate and the channels are significantly reduced over those of conventional single-gate CV profiling. A two-channel OaAs/AlGaAs heterostructure designed for real space transfer applications [1,2] has been successfully profiled using this method. In comparison to standard C-V profiling, the present technique provides much better agreement between the positions of electron concentration peaks determined from the measurement and those expected from calibrated growth thicknesses. While our approach does require a back gate, it could be employed to characterize test structures which incorporate the gate and should be particularly useful for devices in which the back gate is required for normal operation, including real space transfer devices and devices which utilize split top gates to define specific patterns in two-dimensional electron gases. The technique uses standard C-V equipment and does not require complex inversion algorithms, but rather employs the usual parallel plate capacitance model. [1] E.B. Cohen, et al., Appl. Phys. Lett. 70, 2864(1997)[2] E.B. Cohen, et al., 55th Device Research Conf., 1997.

10:20 AM Break

10:40 AM, DD6

Nondestructive Wafer Selection for InGaP/InGaAs/GaAs Heterostructure MESFETs: FUMIAKI HYUGA[1]; Yoshino K Fukai[1]; Yasuro Yamane[1]; Gako Araki[2]; [1]NTT System Electronics Laboratories, 3-1, Morinosato Wakamiya, Atsugi, Kanagawa 243-0198 Japan; [2]NTT Advanced Technology, 3-1 Morinosato Wakamiya, Atsugi, Kanagawa 243-0198 Japan

This paper discusses a nondestructive method for predicting threshold voltage (V_T) of heterostructure field-effect transistors (HFETs). The target devices are the submicron-gate $In_{0.5}Ga_{0.5}P/In_{0.2}Ga_{0.8}As$/GaAs HMESFETs [1] that are attracting much attention as the key devices for high-frequency multi-functional MMICs. The wafer structure of the HMESFETs studied is InGaP (20 nm)/GaAs-cap (5 nm)/InGaP-barrier (10 nm)/InGaAs-channel (Si-doped, 12 nm)/GaAs-buffer (10 nm)/GaAs-substrate. The source and drain regions of the HMESFETs studied are formed by Si-implantation and annealing. The as-grown wafer structures were analyzed by X-ray diffraction (XRD) and spectroscopic ellipsometry (SE). The In composition of the InGaAs channel was first determined from XRD analysis and the thickness of each layer was subsequently determined by SE analysis. This measurement sequence reduced the number of required fitting parameters for SE analysis and increased the accuracy of the thickness determination dramatically. TEM observation confirmed that the thickness of each layer was determined within an error of less than 10%. The electrical characteristics of the as-grown wafers, sheet resistance (R_s) and Hall mobility (u), were determined from eddy current measurements. Carrier concentration in the InGaAs channel (N_d) was derived from these measurements using an InGaP surface potential of 0.5 eV. Pinch-off voltages (V_p) of long-gate FETs were calculated using an N_d decrease factor of 0.52 for activation annealing at 890 ϒC for 0.1 sec. Finally, threshold voltages (V_Ts) were calculated by using the Schottky barrier height of 0.8 eV and taking into account the short channel effect, which was found to depend on the stress under the gates. Since the stress is related to the product of thickness and In composition of the InGaAs channel, their accurate determination is quite important for V_T prediction. After these calculations, 0.12-um-gate HMESFETs were fabricated on 6 wafers with different Si doping concentrations. The measured V_Ts and the calculated V_Ts of these devices were in good agreement within an error of less than 100 mV. And since XD, SE, and eddy current measurements are completely nondestructive, this V_T prediction method is promising for wafer selection. Reference[1] Y. Yamane, K. Onodera, T. Nittono, K. Nishimura, K. Yamasaki, and A. Kanda, IEEE Trans. Electron Devices ED-45, 2229 (1997).

11:00 AM, DD7

$Si_{1-x}Ge_x$ Second Harmonic Generation In-Situ Studies and Ge Segregation Effects : PORSHIA S. PARKINSON[1]; Daeyoung Lim[2]; David E. Brown[1]; JOHN G. EKERDT[1]; Michael C. Downer[2]; [1]The University of Texas at Austin, Department of Chemical Engineering, M/S C0400, Austin, TX 78712 USA; [2]The University of Texas at Austin, Department of Physics, M/S C1600, Austin, TX 78712 USA

$Si_{1-x}Ge_x$ alloys have shown enormous potential as electronic materials for the fabrication of high-speed devices and for optoelectronic applications. In-situ monitoring and control of epitaxial film growth require the description of the hydride reaction pathways and kinetics that underpin growth. One of the key steps in alloy and intrinsic film growth is hydrogen desorption. Hydrogen coverage during growth is also known to influence the surface morphology and growth rate. Second harmonic generation (SHG) allows real-time, in-situ measurement of hydrogen coverage on intrinsic silicon. Thus, SHG has been used by this group to perform hydrogen desorption measurements and growth rate calculations on intrinsic silicon (Xu et al., Appl. Phys. Lett., 71 1376, 1997). The desorption activation energy of 52 kcal/mol calculated from SH intensity measurements of the desorption transient are in agreement with other published temperature programmed desorption (TPD) works. Monitoring the hydrogen coverage during growth and using a second order adsorption and first order desorption model for growth, the disilane reactive sticking coefficient (0.04) and growth rate were calculated, and found to be in excellent agreement with other results. Our current challenge is to develop SHG as a tool to examine the alloy surface. Here, we present studies of the SiGe/Si(100) and the Ge/Si(100) systems in vacuum around the E_1 critical point using SHG. SH intensity decreased with increasing atomic hydrogen coverages on the SiGe/Si(100) surface; the same trend observed on intrinsic Si(100). The SH response to hydrogen coverage on the alloy system might be explainable within the framework of the surface electric field induced second harmonic effect proposed by Xu and Dadap for the H/Si(100) system. In GeH_4 atomic layer epitaxy (ALE) on Si(100), the SH intensity increases with Ge coverage; below 8 ALE cycles. Spectra of the bare $Si_{1-x}Ge_x$/Si(100) surface are also consistent with this observation. The buckled dimers on the surface, or strain induced by the lattice mismatch between the growing Ge film and the silicon substrate may influence the SH response. The desorption of hydrogen from the alloy surface is complicated by the existence of multiple desorption states. Ge is clearly observed to facilitate hydrogen desorption; however, the exact mechanism is disputed. The model proposed by our group convincingly fits the TPD data for hydrogen on Ge/Si(100) (Russell et al., Surf. Sci., 369, 51, 1996). This model provides insight into how hydrogen desorption from the alloy surface may be described. The cornerstones of this model are silicon and germanium monohydride features that are energetically characteristic of the intrinsic surfaces, and hydrogen diffusion from silicon to germanium sites. The diffusion to germanium sites allows more hydrogen to desorb from the lower energy Ge monohydride state. The effect of surface Ge on growth rate and hydride precursor adsorption will be detailed. SHG will be used to establish alloy composition and hydrogen coverage during growth, and thereby account for the changes in growth rate with composition.

11:20 AM, DD8

Determination of the Quality of In-Situ Monitoring of Composition and Thickness by Spectroscopic Ellipsometry Compared with Ex-Situ Techniques: WALTRAUD TERESA TAFERNER[1]; Kurt G. Eyink[1]; Zhuo Meng[2]; Q. Yang[2]; P. C. Yip[2]; Gail J. Browne[1]; Frank Szmulomicz[1]; S. M. Hegde[1]; Scott D. Walck[3]; David H. Tomich[1]; Matthew L. Seaford[1]; W. V. Lampert[1]; [1]Air Force Research Laboratory/Materials & Manufacturing Directorate, MLBM/Surface Interactions Group, WL/MLBM Bldg. 652 Rm 133, 2941 P Street, Suite 1, Wright-Patterson AFB, OH 45433-7750 USA; [2]Case Western Reserve University, Department of Electrical Engineering and Applied Physics, Cleveland, OH 44106 USA; [3]PPG Inds. Inc., Glass Technology Center, Pittsburgh, PA 15238 USA

The ability of Spectroscopic Ellipsometry (SE) to accurately monitor and control the composition and thickness of $Al_xGa_{1-x}As$ for precalibration of growth conditions used in Be:AlGaAs/GasAs Quantum Well Infrared Photodetectors (QWIP) was demonstrated. Layers of $Al_xGa_{1-x}As$ with target compositions of x = 0.1, 0.2, 0.3, 0.4 were grown on GaAs(001) substrates. Instantaneous compositions and growth rates were extracted from the ellipsometric data by using the virtual interface approximation. In addition the overall layer thickness was also determined for each layer by fitting the overall layer to a homogeneous growth spiral. The in-situ results demonstrated that the extracted composition and growth rate had an in-situ precision of less than 1%. X-ray diffraction analysis confirmed the compositions were within 0.02 of the measured compositions. Finally the extracted ellipsometric thicknesses were compared to values measure by High Resolution Transmission Electron Microscopy (HRTEM). Here, SE was shown to be ideally suited for in-situ real-time optimization of growth parameters. A method utilizing Guided Evolutionary Simulated Annealing (GESA) has been developed to control the effusion cell temperatures to achieve the target compositions. Using insitu SE, a precalibration layer was grown to determine the cell temperatures required for a target composition and corresponding growth rates. Subsequently, a series of Quantum Well Infrared Photodetectors (QWIP) were grown and the desired photoresponse of 8 m was attained for $Al_{0.3}Ga_{0.7}As$ and GaAs quantum well width of 16 ML.

11:40 AM, DD9

In-Situ Non-destructive Characterization of Ultrathin Oxynitride Films Grown on Si By UHV Contactless Capacitance-Voltage Method: TOSHIYUKI YOSHIDA[1]; Tamotsu Hashizume[1]; Hideki Hasegawa[1]; Takamasa Sakai[2]; [1]Hokkaido University, North13, West 8, Sapporo, Hokkaido 060-8628 Japan; [2]Dainippon Screen Manufacturing Co., Ltd., 322 Furukawa-cho, Hazukashi, Fushimi-ku, Kyoto 612 Japan

For continued down-scaling of Si CMOS devices for the G-bit order DRAMs as well as for introduction of new quantum devices such as Si-based single electron transistors, formation of ultrathin insulating films with good electrical properties on Si is strongly required. One promising approach for this is use of an UHV-based insulator growth/processing system. Here UHV-based non-destructive monitoring and characterization techniques become indispensable for optimization of growth/processing steps. However, there has been no well-established method for characterizing the electronic properties of free surfaces and ultrathin insulating films/silicon interfaces which are directly related to device performance. This paper presents for the first time in-situ electronic characterization of ultrathin oxynitride/silicon interfaces by a contactless UHV capacitance-voltage (C-V) measurement technique. In this method, a narrow UHV-gap (300-400nm) is maintained between the electrode and sample surface by a piezo-mechanism with capacitance feedback from the three parallelism electrodes, thereby allowing standard MIS assessment in-situ in UHV without suffering from the tunneling leakage problem. This system is also connected with the UHV-based multi-chamber growth/fabrication facility which contains X-ray photoelectron spectroscopy (XPS), UHV photo luminescence (PL) and UHV scanning tunneling microscopy (STM) chambers for in-situ and non-destructive surface characterization. Wafers used in the present study were n-type Si with a carrier concentration of $1\text{-}2x10^{15}cm^{-3}$. We prepared a hydrogen terminated surfaces as the initial surface, since it provides an atomically flat and extremely clean surface. This initial Si surfaces prepared by BHF/NH_4F(40%) related treatment showed UHV C-V curves with a large hysteresis at negative voltage region and completely flat at positive voltage region, indicating presence of a strong Fermi level pinning due to the high-density of surface states. XPS analysis indicated that a Fermi level was pinned at 0.65eV above the valence band edge on this surface. In-situ PL analysis clearly showed the existence of a discrete type of surface states. After formation of ultrathin oxynitride film (thickness of 2.0nm-3.5nm) by ECR- N_2O plasma process, pinning-free C-V curves were successfully obtained. From the Terman analysis using UHV C-V curves as well as the in-situ PL analysis, very wide and U-shaped surface state distributions with low density were obtained after oxynitridation. Root mean square (RMS) value of the surface roughness was found to be within 0.7nm. XPS analysis showed that the ultrathin oxynitride film almost consisted of pure SiO_2 component with formation of a nitrogen-rich interfacial layer as indicated by the N1s spectra. Presence of such a nitrogen-rich interfacial phase was found to be responsible for the observed excellent electronic interface property.

12:00 PM, DD10

Ultraviolet Absorption Sensors for Precursor Delivery Rate Control in Metalorganic Chemical Vapor Deposition of Multiple Component Oxide Thin Films: WILLIAM J. DESISTO[1]; Brian J. Rappoli[2]; [1]Naval Research Laboratory, Electronics Science and Technology Division, Code 6861, Washington , DC 20375-5347 USA; [2]Naval Research Laboratory, Chemistry Division, Code 6116, Washington, DC USA

Film composition control during metalorganic chemical vapor deposition (MOCVD) of mixed metal oxides is a significant challenge because of the chemical and physical nature of the metalorganic precursors employed in the process. We report the development of sensors, based on ultraviolet absorption spectroscopy, for measuring the concentrations and controlling the molar flow rates of 2,2,6,6-tetramethyl-3,5-heptanedionate (thd) complexes of yttrium, lanthanum and copper, in the gas delivery system of a MOCVD reactor. The gas delivery system was modified to incorporate UV absorption sensors located between individual bubblers and the mixing gas manifold. Each sensor, in series with the respective bubbler, provided real-time in-situ concentration measurement of the individual precursor. Spectral data were acquired for individual precursors at four second intervals using dual-beam spectrograph/photodiode arrays. The measured absorption for individual precursors was used to determine concentration in the gas stream using the Beer-Lambert relation and molar extinction coefficients determined from solution data. Using the measured concentration, feedback control of the yttrium and copper thd complex molar flow rates was achieved by adjusting the carrier mass flow rate through the bubbler. The precursors were loaded into 200 cc stainless steel bubblers and mixed with either stainless steel helices or glass beads to provide a finely divided precursor distribution and enhance carrier gas saturation. Bubbler temperatures for Y $(thd)_3$ and $Cu(thd)_2$ were between 120 and 135ϒC. $La(thd)_3$ was heated to between 170 and 190ϒC. Under typical conditions, broad spectral peaks were observed for these complexes between 250 and 310 nm, with absorbance values between 0.1 and 0.3. Baseline stability and drift were between 0.001 and 0.002 absorbance units resulting in large signal-to-noise ratios. The uncontrolled molar flow rates varied approximately 3 to 4 % above and below the mean molar flow rate. Applying feedback control, the molar flow rates were controlled to better than one half of one percent of the desired molar flow rate. Mixed Y-Cu-O films were grown to compare gas phase composition to film composition. Films were grown on (100) MgO substrates at temperatures between 600 and 800ϒC. Comparison of film composition to gas composition indicated that copper was preferentially incorporated into films during film growth.

Friday AM, June 26, 1998

Session EE. Epitaxial Growth

Room: E303
Location: Thornton Hall

Session Chairs: Hong Q. Hou, EMCORE West, Albuquerque, NM; Phil W. Yi, Kwangju Institute of Science and Technology, Kwangju 506-303 Korea

8:20 AM, EE1+

Model for the Morphology of Homo-Epitaxial Vicinal (100) III-V Surfaces: COEN A. VERSCHUREN[1]; Maarten R. Leys[1]; Rene T.H. Rongen[1]; Bert Vonk[1]; Joachim H. Wolter[1]; [1]Eindhoven University of Technology, Dept. of Physics, P.O. Box 513, Eindhoven, Noord-Brabant 5600 MB Netherlands

Vicinal substrates are widely used to fabricate semiconductor devices. The surface steps are intended to facilitate smooth growth by step flow. Nevertheless, numerous papers report bunching of steps when strained layers are grown on vicinal surfaces, for which different mechanisms have been proposed [1]. Bunching, however, can also occur during homo-epitaxial growth on vicinal (100) III-V surfaces, especially those with mixed steps. When the step flow is disturbed, e.g. by a wafer edge or by a mask edge in Selective Area Epitaxy, this leads to a distinct surface corrugation extending from the edge [2]. So far, no satisfactory explanation has been given for these phenomena. We have systematically studied the effect of the different types of surface steps on t he (100) InP morphology as a function of growth conditions in Chemical Beam Epitaxy. Misorientations of 0 to 2° towards (110), (111)A and (111)B have been used. The growth temperature was varied from 500 to 530 °C at V/III ratios from 1.9 to 7.6. On substrates containing no steps or only A type steps, we observe mirror-like surfaces but characteristic defects are always present. We attribute the origin of these defects to clustering of indium adatoms. When sufficient chemically active B type steps are present, clustering is prevented and almost no defects are found. The surface is smooth for low step densities and becomes somewhat rougher with increasing step density due to bunching of steps. From any edge a ripple pattern extends over tens of microns in the B step propagation direction. For a substrate with mixed, i.e. both A and B type steps, the surface roughening and the edge effect are much more pronounced and depend strongly on growth conditions. Vicinal (100) III-V surfaces are metastable, i.e. they can minimize their surface free energy by breaking up into stable facets. The dimensions of these facets are determined by the supersaturation during growth. By also including 2 ML high A type and 1 ML high B type steps [3], we have derived a general model for the morphology of homo-epitaxial vicinal (100) III-V surfaces. We will show that it successfully explains all features on vicinal (100) InP grown by CBE, including the dependence on growth conditions. In particular, we can quantitatively describe the structure and development of the pronounced edge effect using only one free dimensionless parameter. Finally, the applicability of the model to other materials systems will be discussed. [1] J. Tersoff, Y.H. Phang, Z. Zhang and M.G. Lagally, Phys. Rev. Lett. 75, 14 (1995) 2730-2733. [2] H. Heinecke, A. Milde, R. Matz, B. Baur and R. Primig, Physica Scripta Vol. T55 (1994) 14-19. [3] C.A. Verschuren, M.R. Leys, Y.S. Oei, C.G.M. Vreeburg, H. Vonk, R.T.H. Rongen and J.H. Wolter, J. Crystal Growth 170 (1997) 650-654.

8:40 AM, EE2

Temperature and Deposition Rate Dependence of Morphological Instability in InAs/GaSb Heterostructures: MARK E. TWIGG[1]; B. R. Bennett[1]; R. Magno[1]; [1]Naval Research Laboratory, Code 6812, 4555 Overlook Avenue, S.W., Washington, DC 20375-5320 USA

In order to grow the optimal strained layer InAs/$Ga_{1-x}In_xSb$ superlattice for a specific infrared detector application, the thickness and composition of the layers are tailored to achieve the designed bandgap. We have found, however, that even for the small-misfit (0.6%) InAs/GaSb heteroepitaxial system, strain-relieving surface undulations may occur. The presence of such undulations lead to variations in layer thickness, which may in turn degrade the electro-optical properties of such a superlattice. Using transmission electron microscopy, we examined several different InAs films grown on (100) GaSb by molecular beam epitaxy, with thicknesses ranging from 3 to 40 monolayers (ML). The growth conditions included deposition rates of 0.09, 0.06, and 0.03 ML/s, and temperatures of 400, 425, 450, 475 and 500 ℃. We have found that the tendency for morphological instability is enhanced by higher growth temperatures, but suppressed by higher deposition rates. The competing effects of growth temperature and deposition rate can be evaluated given a knowledge of the indium diffusion length as a function of growth temperature and As4 partial pressure. The indium diffusion length is seen to increase with temperature and decrease with the As_4 partial pressure (and hence decrease with the deposition rate) [1]. Indeed, we have found that morphological instability for an InAs layer grown on (100) GaSb only occurs when the ratio of the indium diffusion length squared to kT, $(L^2)/kT$, is greater than 500,000 (cm^2)/erg (where k is Boltzman's constant, and T is the absolute temperature) [2]. The ratio $(L^2)/kT$ increases monotonically with temperature and decreases monotonically with deposition rate, as does the tendency for morphological instability. From reflection electron microscopy and atomic force microscopy observations, the wavelength of the surface undulations were found to range from 100-800 nm with an amplitude of 1 nm. The small amplitude and aspect ratio of these undulations suggest that morphological instability in InAs/GaSb may be understood in terms of the linear stability theory of Spencer et al.[3]. Indeed, the form of the threshold ratio $(L^2)/kT$ can be derived from linear stability theory. Our results differ from the predictions of Spencer et al., however, in one important respect: that the InAs layer thickness appears to have no effect on the onset of morphological instability. In other words, no kinetic critical thickness is observed. [1] X. Q. Shen and T. Nishinaga, J. Cryst. Growth 146, 374 (1995). [2] M. E. Twigg, B. R. Bennett, and R. Magno, submitted to J. Cryst. Growth. [3] B. J. Spencer, P. W. Voorhees, and S. H. Davis, J. Appl. Phys. 73, 4955 (1993).

9:00 AM, EE3+

Optical Waveguides Fabricated From II-VI Semiconductors Using Low-Temperature MOMBE Selective Growth : AKIO UETA[1]; Adrian Avramescu[1]; Katuhiro Uesugi[1]; Ikuo Suemune[1]; Hideaki Machida[2]; Norio Shimoyama[2]; [1]Hokkaido University, Research Institute for Electronic Science, Kita-12, Nishi-6, Kita-ku, Sapporo, Hokkaido 060-0812 Japan; [2]Trichemical Laboratory, Uenohara 8154-217, Kitatsurugun, Uenohara, Yamanashi 409-01 Japan

Optical interconnections are widely studied to overcome the signal delay problems caused by the parasitic capacitance of electrical wiring in integrated circuits and to improve the performance of computers. Optical interconnections also have the possibilities of lower power dissipation and 3-D integration. Toward the realization of optical interconnections on chips, fabrications of minute optical devices and optical waveguides are necessary, and we studied optical waveguide structures by selective growth of ZnSe and ZnS on (001)GaAs with metalorganic molecular-beam epitaxy (MOMBE). To fabricate optical devices, low growth temperature is necessary to prevent the problems of interface diffusion, damage on Al electrical wiring and degradation of electronic devices already been integrated. II-VI semiconductors can be grown at much lower temperatures than other semiconductors, and the waveguide structures studied in this work were grown at 350℃ or 400℃. The precursors used for the growth were diethyl zinc (DEZn), ditertiarybutyl selenide (DtBSe) and ditertiarybutyl sulfide (DtBS). The carbonaceous films directly deposited and patterned by electron-beam irradiation in a scanning electron microscope (SEM) were used as the masks for the selective growth.[1)] The thicknesses of these ZnS/ZnSe/ZnS waveguide structures were decided by a refractive index calculation and one-dimensional and 2-dimensional analyses not to leak lights into GaAs substrates that has higher refractive index than ZnSe and ZnS, and they were 300 nm for the ZnS cladding layers and 80 nm for the ZnSe waveguide layer. The optical confinement factor in the ZnSe layer of this structure is estimated to be 73.9 % and 60.5 % at the wavelengths of 460 nm and 500 nm, respectively. The waveguide structures grown in the [110] direction were consisted of (311)B and vertical (-110) facets, and the cross section was a house like shape. The fluctuation of the side facets in the 1 micron wide waveguides were controlled within 30 nm. To couple the optical wave into the waveguide structures, the GaAs (111)A facets were prepared with photolithography and etching before the growth. The waveguide structures were fabricated overlaying this GaAs (111)A facets and lights reflected from the GaAs (111)A facets were coupled to the waveguide structures. The optical wave guiding was imaged in this way, and this verified the effectiveness of these selectively grown structures for optical interconnections. Reference: 1) A. Ueta, A. Avramescu, K. Uesugi, I. Suemune, H. Machida and N. Shimoyama : Jpn. J. Appl. Phys. Vol. 37 (1998) (to be published)

9:20 AM, EE4+

Growth of ZnCdSe/ZnSe QW Structure on Hexagonal (Zn,Mg)(S,Se) Bulk Substrates: WEICHENG LIN[1]; Maria C Tamargo[1]; Brian J. Fitzpatrick[2]; Jeffrey Steiner[3]; [1]City College of New York, Chemistry Department, Convent Ave. & 138th Street, New York, NY 10031 USA; [2]Optical Semiconductor, Inc., 8 John Walsh Blvd., Peekskill, NY 10566 USA; [3]City College and Graduate School of CUNY, Earth and Atmospheric Sciences, Convent Ave. & 138th Street, New York, NY 10031 USA

Growth of wide bandgap II-VI lasers on native (II-VI) bulk substrates eliminates many problems associated with heterovalent II-VI/III-V growth. Most attempts at using native substrates have assumed that cubic crystals are preferred for device applications. However, cubic wide bandgap II-VI crystals tend to exhibit defects, such as twins. On the other hand, it has been observed that II-VI crystals with preferred hexagonal structures, such as ZnS or CdS, can be grown with a near absence of twins. Dislocation motion in hexagonal structures is also expected to be slower, which may be helpful in reducing degradation. Bulk ternary and quaternary alloys of binary compounds that have different preferred phases will assume one phase or the other depending on the composition. In this work, we design hexagonal wide bandgap II-VI substrates that

have the appropriate bandgaps for blue-green laser applications. We also perform MBE growth of ZnSe-based layers and quantum well (QW) structures and investigate their properties. We have grown hexagonal (Zn,Mg)(S,Se) bulk crystals with 12%Mg and 8% S by the zone melting technique. Powder diffraction was used to confirm the structure, which has a lattice constant a_o of 4.0128 Angstrom and c_o/a_o ratio of 1.6335. Cleavage surfaces having (11-20) orientation were identified using single crystal x-ray scans. The high crystalline quality of the substrates was also confirmed by the x-ray measurements. The 77K photoluminescence (PL) shows a dominant bandedge emission and a near absence of deep levels. We have grown single layers of ZnSe on these (11-20) surfaces by MBE. The cleaved surfaces were degreased prior to introduction into the chamber. Thermal treatment before growth was made by heating the sample under a Se flux to 450 °C, to remove a native oxide layer. The single crystal x-ray scans of the layers were indistinguishable from those of the substrate, suggesting a similar crystalline structure. 77K PL measurements show a near bandedge peak at 2.8 eV and a dominant peak at 2.6 eV, assumed to be the so-called Y-line, which suggests the presence of defects. A second sample was used to grow a quantum well structure, consisting of a ZnSe barrier layer ~2 mm thick, a $Zn_{0.8}Cd_{0.2}$Sewell, nominally 10 nm thick, and a top ZnSe barrier layer ~100 nm thick. A more thorough heating of the substrate (510 °C) was performed on this sample to ensure a higher quality substrate/epi interface. No change in the RHEED pattern occurred upon growth initiation. The room temperature and 77K PL spectra for this structure are dominated by a strong sharp peak corresponding to the QW emission. No deep level emission is observed. Double crystal x-ray rocking curves present only one peak from the layer structure ~100 arcsec from the substrate peak. Although no unequivocal identification of the crystal structure of the epitaxial layers has been obtained, the similarity to the substrate characteristics and the high quality of the layer properties suggest that it is also hexagonal. Other measurements such as TEM and Raman spectroscopy are being pursued to establish the crystal structure.

9:40 AM, EE5+

Chalcopyrite Structure $ZnSnP_2$ Grown by Sas Source Molecular Beam Epitaxy: GEORGIY A. SERYOGIN[1]; Sergey A. Nikishin[1]; Sebastien Francoeur[1]; Henryk Temkin[1]; Toni D. Sauncy[3]; Nikolai Nikolaevich Faleev[4]; Alexander Mintairov[4]; Bruce Parkinson[2]; [1]Texas Tech University, Department of Electrical Engineering, Lubbock, TX 79409 USA; [2]Colorado State University, Department of Chemistry, Fort Collins, CO 80523 USA; [3]Texas Tech University, Department of Physics, Lubbock, TX 79409 USA; [4]A. F. Ioffe Physico-Technical Institute, 26 Polytechnicheskaya St., St.Petersburg 194021 Russia

The II-IV-V_2 compound $ZnSnP_2$ is isoelectronic with a III-V alloy $In_{0.5}Ga_{0.5}P$. It can be prepared, depending on growth conditions, in two different crystalline structures - chalcopyrite and sphalerite. The two structural modifications have different band gaps of 1.24 eV and 1.66 eV, respectively. The existence of such a difference gives rise to a possibility of forming heterostructures and makes $ZnSnP_2$ a very interesting material for photovoltaic and nonlinear optics applications. However, the possibility of two crystalline modifications and a high probability of forming interfacial compounds such as Zn_3P_2 and Zn_3P_4 at low substrate temperatures, makes it difficult to obtain single phase epitaxial layers. Having a bulk lattice constant of 5.651 angstrom, very similar to that of GaAs, lattice matched layers of $ZnSnP_2$ can, in principle, be grown on GaAs substrates. Single layers of $ZnSnP_2$ were grown by gas source molecular beam epitaxy on GaAs(100) using PH_3 as phosphorus source. We used a custom designed MBE apparatus that allows for excellent control of the growth temperature and the group II/IV flux ratio. Samples were evaluated by high resolution X-ray diffraction, Raman spectroscopy, secondary ion mass spectroscopy (SIMS), photoluminescence and atomic force microscopy. Growth conditions were investigated as a function of substrate temperature, from 300°C to 360°C, and the Sn/Zn flux ratio. The sticking coefficient of zinc is one of the factors limiting the growth rate at higher substrate temperatures. We were able to supply a Zn flux sufficient to maintain the growth rate of at least 0.25 um/hr at substrate temperatures of 360°C. The stoichiometry of epitaxial layers was confirmed, to within ~1%, using SIMS. The growth rate was found to be linearly dependent on the Sn flux, under a constant Sn/Zn flux ratio. With increasing Sn/Zn flux ratio, by 5% to 10%, we observe a transition between two epitaxial phases. The initial phase has a negative lattice mismatch with respect to GaAs, on the order of 0.4 %. With increasing Sn/Zn flux the growth switches to a second phase which has a small positive lattice mismatch, varying from 0 to 0.01 %. The presence of thickness oscillations in high resolution X-ray patterns demonstrates the planar structure and high structural quality of epitaxial layers. Photoluminescence measurements were performed on both types of samples. Only samples with a positive mismatch produce room temperature luminescence. Its peak position, indicative of the bandgap, is at 1.36 eV. Raman measurements show the presence of a strong A1 chalcopyrite mode in samples with a positive mismatch. In samples with a negative mismatch the A1 mode is weak and shifted to low energies. Microscopic structure of these layers is being determined.

10:00 AM Break

Friday AM, June 26, 1998

Session FF. Novel Light Emitters

Room: E303
Location: Thornton Hall

Session Chairs: Hong Q. Hou, EMCORE West, Albuquerque, NM; Phil W. Yi, Kwangju Institute of Science and Technology, Kwangju 506-303 Korea

10:20 AM, FF1+

Erbium-Doped Polysilicon and Dielectric Stack Microcavity for Light Emitting Applications: THOMAS D. CHEN[1]; Anuradha M. Agarwal[1]; Jurgen Michel[1]; Lionel C. Kimerling[1]; [1]MIT, Materials Science and Engineering, 77 Massachusetts Avenue 13-4153, Cambridge, MA 02139 USA

Erbium-doped silicon (Si:Er) has been widely studied as a possible light emitter (λ=1.537 μm) for integrated silicon microphotonics technology. Although single crystal Si:Er has been the focus of many studies in recent times, erbium-doped polysilicon (poly-Si:Er) allows higher concentrations of erbium incorporation and the ability to use a stack dielectric microcavity to increase the luminescence intensity through spontaneous emission enhancement. The microcavity enhancement will especially allow higher light emission at room temperature. This microcavity consists of two dielectric stack mirrors, separated by a light emitting active layer. The mirrors are comprised of alternating layers of amorphous silicon and silicon dioxide, which are compatible with standard CMOS technology. Because crystalline silicon cannot be deposited on such a structure, poly-Si:Er must be used as the light emitting active layer. Combined with polysilicon waveguide technology, poly-Si:Er microcavity emitters allow the possibility for multiple levels of optical interconnection in a silicon microphotonic system. We have studied erbium/oxygen-implanted (10^{20} cm^{-3} and $5x10^{20}$ cm^{-3} respectively) silicon films that were amorphously deposited on 1 μm of oxide and subsequently recrystallized by a series of thermal treatments. Photoluminescence (PL) and glancing angle x-ray diffraction (XRD) were used to characterize the poly-Si:Er. Isochronal anneals for 30 minutes and isothermal anneals at 600ºC showed that the erbium luminescence intensity was directly related to the degree of recrystallization during the anneal. Hydrogen passivation of dangling bonds further increased the luminescence intensity to about one half of the intensity found in some single crystal material. A Si/SiO_2 stack dielectric microcavity tuned to the Er emission wavelength was fabricated by electron-beam deposition and annealed under conditions that yielded the best poly-Si:Er luminescence. After the recrystallization anneal, the microcavity was found to have a resonance at 1.539 μm and a cavity quality factor of ~300. The microcavity was used to enhance the Er spontaneous emission rate in order to increase the luminescence intensity. The enhancement factor is directly related to the quality factor of the microcavity and thus depends on the number of dielectric layers that comprise the microcavity mirrors. Electroluminescence from poly-Si:Er diodes in forward and reverse bias will be presented to demonstrate functionality as resonant cavity LEDs.

10:40 AM, FF2+

Epitaxial Er-Doped $BaTiO_3$ and Its Luminescent Properties: ANDREW TEREN[1]; Gregory M. Ford[1]; BRUCE W. WESSELS[1]; [1]Northwestern University, Materials Science and Engineering, 2225 N. Campus Dr., Evanston, IL 60208 USA

There is considerable interest in the development of epitaxial $BaTiO_3$ ferroelectric thin films for integrated optic and micro-photonic applications. Recently we have shown that Er-doped $BaTiO_3$ waveguides exhibited stimulated emission upon optical pumping. Further increases, however, in the luminescence efficiency are required if it is to be used as an optical gain medium. The luminescent properties of Er-doped $BaTiO_3$ thin films prepared by MOCVD were investigated. It was noted that the characteristic Er-related luminescence intensity at 1.54 microns depended upon both deposition conditions and post-deposition processing. To determine the factors influencing the intensity, the Er-doped films were annealed at high temperatures in oxygen. The characteristic luminescence intensity increased as much as twenty-fold upon annealing. The increase in intensity is tentatively attributed to the activation of the Er centers. The influence of annealing on the lifetime of the optically excited Er center was also studied using transient photoluminescence. Radiative lifetimes of 8 ms were measured. A model for the luminescence efficiency was developed and will be described.

11:00 AM, FF3+

Single-Layer Polymer Blend Organic Light Emitting Diodes with Electron Transport Polymers: K. A. Killeen[2]; T. R. Hebner[1]; F. Pschenitzka[1]; M. H. Lu[1]; M. E. Thompson[2]; J. A. STURM[1]; [1]Princeton University, Dept. of Electrical Engineering, Engineering Quadrangle, Princeton, NJ 08544-5263 USA; [2]University of Southern California, Department of Chemistry, Los Angeles, CA 90089 USA

One structure for the wet processing of organic light emitting diodes (OLEDS) which has exhibited great promise are polymer blends, in which emissive, and carrier transport agents are blended into a host polymer. Most previous work focused on blends of the hole transport polymer poly-vinylcarbazole (PVK) with electron transport small molecule of 2-(4-Biphynlyl)-5-(4-tert-butylphenyl)-1,3,4-oxadiazole (PBD)[1]. However, concerns about the recrystallization of PBD and other small molecule electron transport materials make it desirable to develop an electron transport polymer (ETP) for use in polymer blends. Previous work in this direction has focused on multi layer devices [2,3] but to our knowledge, no single-layer polymer blend devices using ETP have been made. In this work we describe the preparation and use of an electron transport polymer in such single-layer devices. In this work we focus on polymers with pendant oxadiazole groups similar to PBD. A 2,5-diaryl oxadiazole pendant polymer (POXD) was prepared by the substitution of the chloride groups in poly(vinylbenzyl chloride) (Aldrich; 60/40 mixture of 3- and 4- isomers; Mw ca. ~55,000) with 2-(hydroxyphenyl)-5-phenyl-1,3,4-oxadiazole in basic DMF. ^{1}H NMR spectroscopy of the oxadiazole pendant polymer shows complete substitution of the benzyl chloride groups and we observe no chlorine in the elemental analyses of the polymer. Single-layer devices were successfully fabricated on indium tin oxide (ITO) coated glass using Mg:Ag/Ag electrodes. The single organic layer was deposited via spin coating with the hole transport material PVK, the electron transport material POXD and the emissive dye coumarin 6 (C6) along with PVK/PBD/C6 control devices. Devices had turn-on voltages of ~10-13V, emission spectra matching that of C6 dye (peak = 493 nm), and a quantum efficiency of ~0. 18%. The optimum ratio of hole transport (PVK) to electron transport (POXD) was found to be ~5:2, which is surprisingly similar to the optimal ratio of PVK:PBD in the related molecularly doped devices. Work in progress includes, the continuing optimization of the PVK/POXD/C6 blend devices and examination of new devices with molecular hole transport materials doped into the polymeric electron transport materials. In addition, we will report on the phase segregation in the polymer blend layers utilizing techniques in atomic force microscopy and transmission electron microscopy. This work was supported by NSF and DARPA (1464-967). 1 . C.C. Wu, J.C. Sturm, R. A. Register, J. Tian, E.P. Dana, and M.E. Thompson IEEE, Transactions on Electron Devices 1997, 44, 1269-1280. 2. E. Buchwaid, M. Meier, S. Karg, P. Posch, H. Schmidt, P. Strohriegl, W. Reiß, and M. Schwoerer Adv. Mater. 1995, 7, 839-842. 3. M. Greczmiel, P. Strohriegl, M. Meier, and W. Brutting Macromolecules 1997, 30, 60426046.

11:20 AM, FF4+

Carrier Transport Mechanisms in Organic Electroluminescent Devices: JUN SHEN[1]; Jie Yang[1]; Ji-Hai Xu[2]; Franky So[2]; H.-C. Lee[2]; [1]Arizona State University, Dept. of Electrical Engineering and Center for Solid State Electronic Research, P.O. Box 875706, Tempe, AZ 85287 USA; [2]Motorola, Inc., Phoenix Applied Research Center, 2100 E. Elliot Rd., Tempe, AZ 85284 USA

We will review the current status of the theoretical understanding of carrier transport mechanisms in organic electroluminescent devices (OEDs). Existing theories are critically compared with available experimental data from various laboratories. The applicability of contact-limited (thermionic emission, Fowler-Nordheim tunneling, etc.) and bulk-limited (trap-charge limited (TCL), field-mobility dependence, etc.) to various conditions is discussed. Then we present our theoretical results on the double-carrier injection devices (OEDs) under trap-charge limited conditions. Our theoretical work consists of two parts: analytical and numerical studies. In our analytical study, we extended previous single-carrier TCL theories to double-carrier case. Several new pieces of physics, which have been puzzling researchers in the field, are revealed and explained using the formula. A new region in the experimental current-voltage characteristics is identified and postulated to be the internal photo de-trapping (IPD) region. Recently, we also developed a numerical model taking into account the main ingredients in the OED TCL transport. Current-voltage characteristics, detailed energy and charge profiles are generated, and some physical insights are gained. For example, we developed clear pictures on the mechanisms that determine the location of the recombination zone, the double v.s. single carrier injection current enhancement, the temperature dependence, etc. Interesting doping effects and contact effects are also studied. In the talk, we will present these results and discuss their relevance with the experimental data.

11:40 AM, FF5

Late News